MULTI-GIGABIT WIRELESS DATA TRANSFER USING THE 60 GHZ BAND

Hans Kristian Soltveit

On behalf of the WADAPT working group

Wireless Allowing Data And Power Transmission

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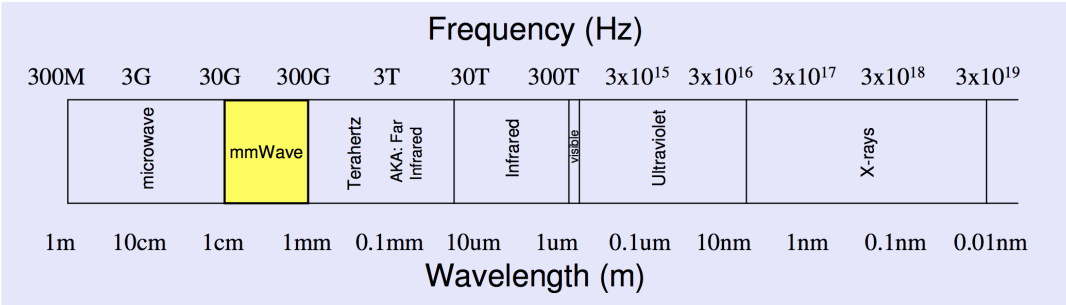
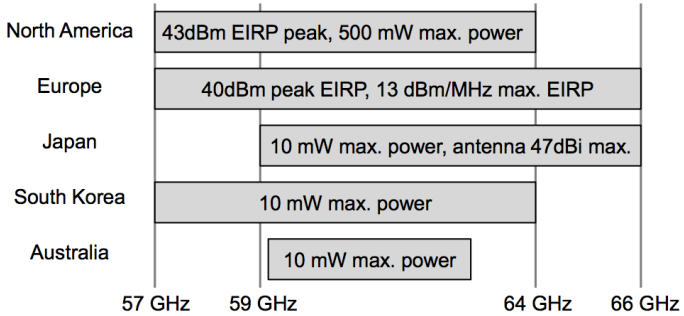
OUTLINE

- ✧ Introduction to millimeter Wave
- ✧ Features of the 60 GHz Band
- ✧ Practical Opportunities
- ✧ Application in HEP
- ✧ Proposed Readout Concept
- ✧ Heidelberg ASIC
- ✧ Other developments:
  - ✧ Antenna
  - ✧ Leti ASIC
  - ✧ Heidelberg tests
- ✧ Summary and Outlook

The mm-Waveband

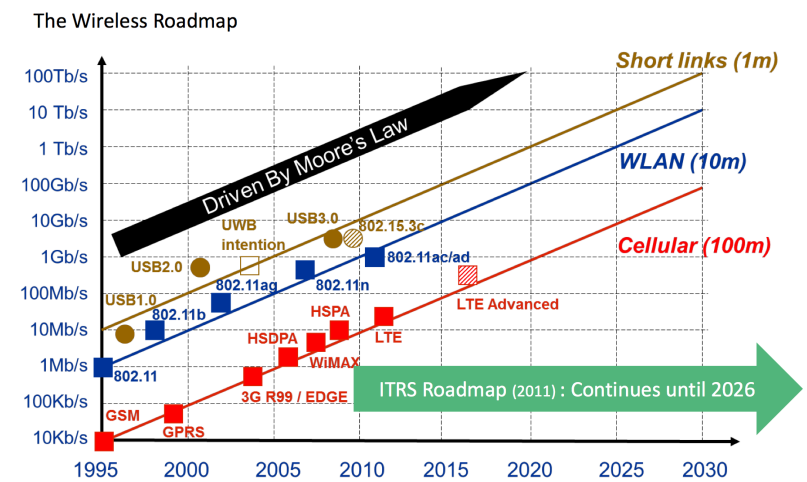
- The mm-Wave is defined as the band between 30 GHz (10mm) to 300 GHz (1mm)
- In 2001, the Federal Communication Commission (FCC) opened up the 57 - 66 GHz band. In 2003 several other bands followed (Automotive 77 GHz Radar, 94 GHz imaging, THz spectroscopy > 100 GHz and so on….).
- This due to the "technological advance" and in order to "facilitate the commercialization of the Millimeter Wave Band"
- Triggered huge interest from Industry and Research center/Universities etc.
- Energy propagation in the 60 GHz band has some unique characteristic that makes some interesting features.
- This allows a higher Effective Isotropic Radiated Power (EIRP)





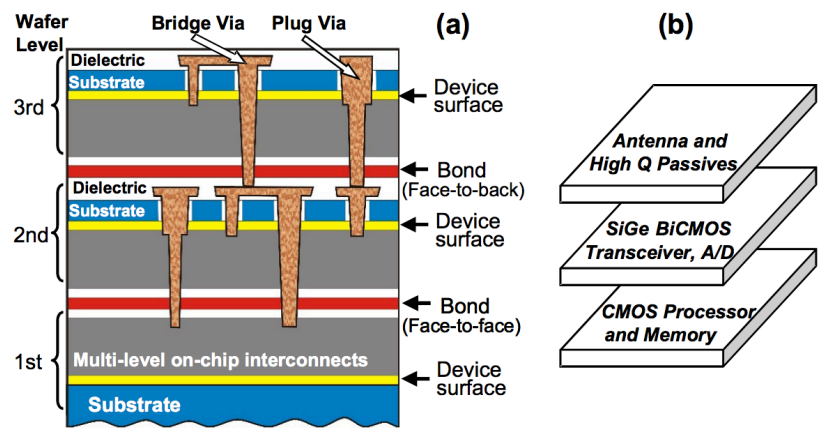
The mm-Waveband

- ✧ Demand for high capacity continues to increase with an incredible speed.
- ✧ An ongoing race: technology and application developers have pushed into higher and higher bandwidth.



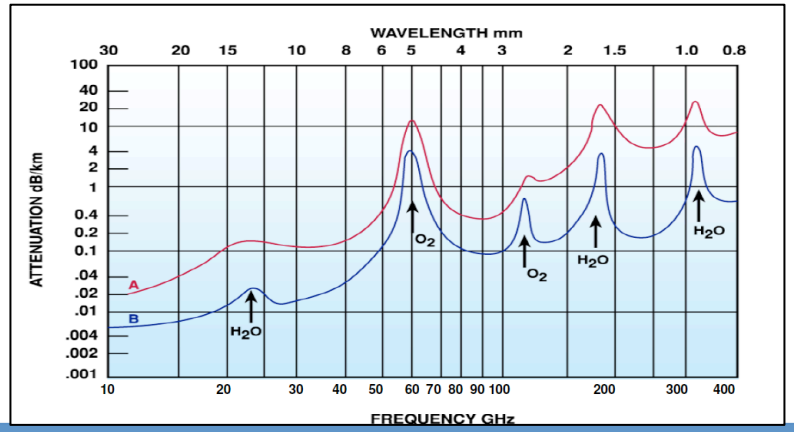
Performance driven applications and high level of integration:

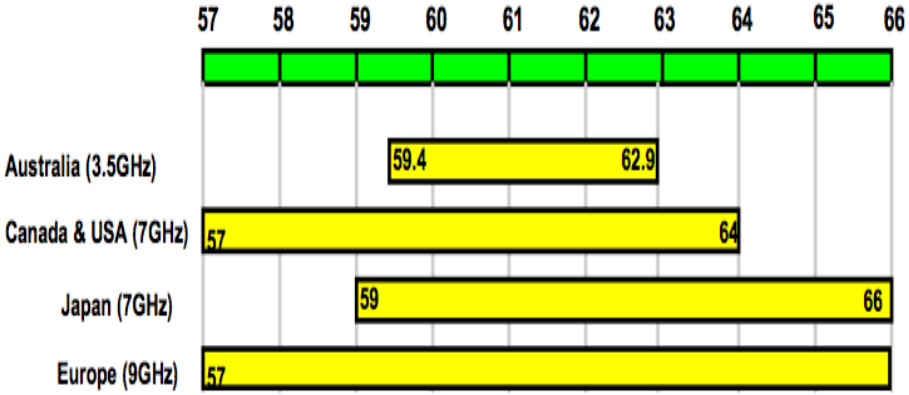
- ✧ Heterogeneous Integration advantage
  - ✧ Allow to use technology optimized according to their function



Features of the 60 GHz Band

- ✧ Unlicensed Spectrum: 4-9 GHz bandwidth available world-wide
- ✧ Can send Gigabits/s of data over short distance (0.01-100 m)
- ✧ Highly secure and low interference probability: Short transmission distance, oxygen absorption, narrow beam width and attenuation through materials.
  - ✧ Reuse of frequency
- ✧ Placement: High flexibility, reduced complexity of cabling, material budget.
- ✧ High frequency: Small form factor.
- ✧ High transmit power: 40 dBm EIRP (Equivalent Isotropically Radiated Power)
- ✧ Mature techniques: Long history in being used for secure communication.





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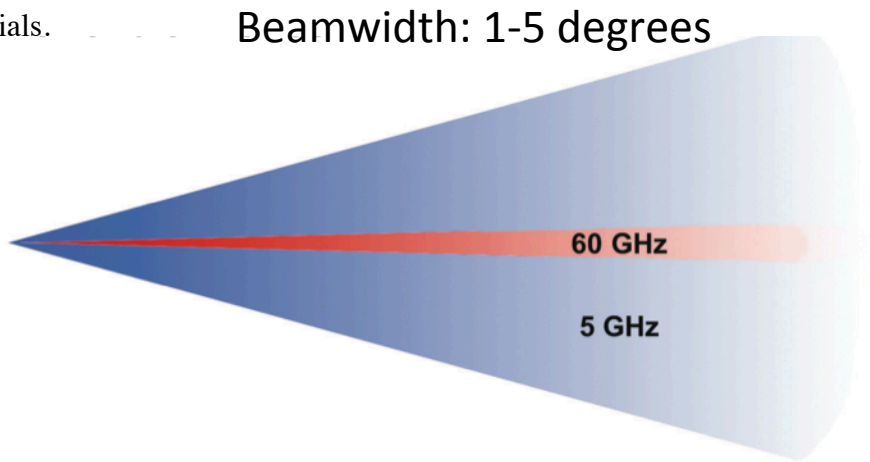
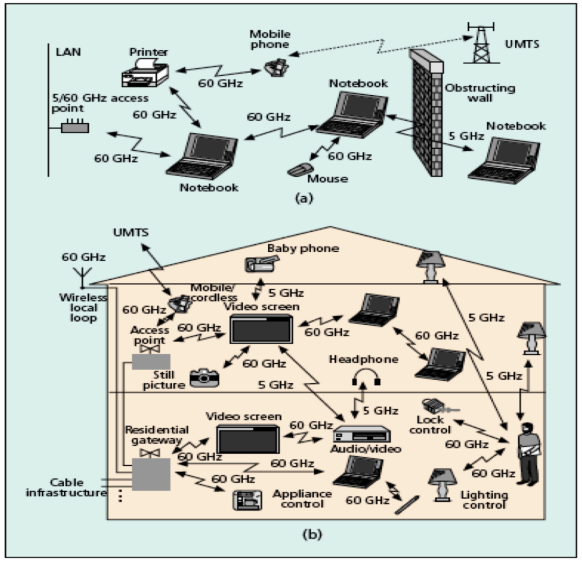


These Features:

Narrow beam-width, high bandwidth, high interference immunity, high security, high frequency reuse, high density of users, high penetration loss, ultra low latency and low material budget

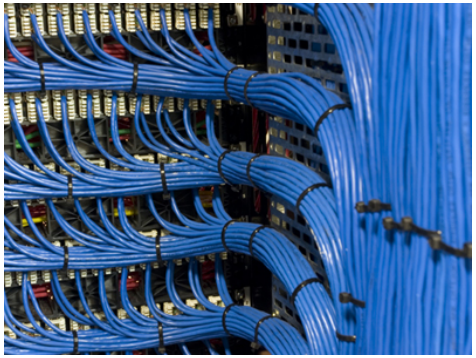
makes the 60 GHz band an **excellent choice** for high data transfer in a closed short range environment as the **detector environment**.

Practical Opportunities

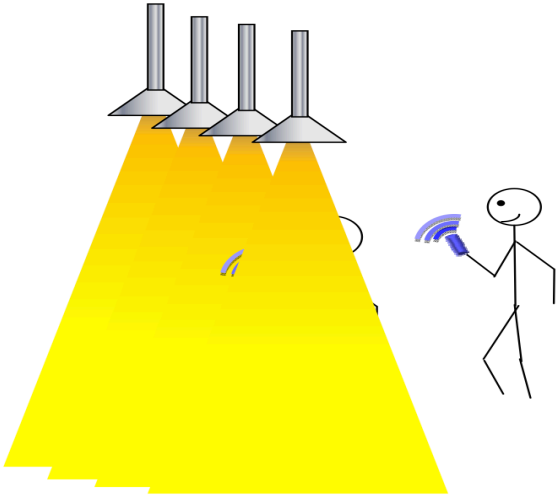


- ✧ Interconnectivity of media devices
- ✧ High data rates, fast file transfers
- ✧ Streaming uncompressed HD content

Replace Gigabit Ethernet Cables



- ✧ Copper resistance increase
- ✧ Easy reconfiguration
- ✧ Lower power
- ✧ Reduction in cable number
- ✧ Cooling requirement



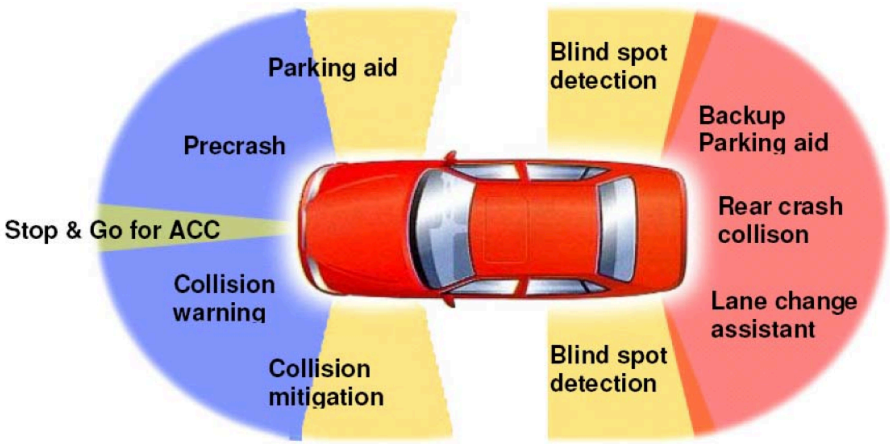
"Showered" with information

- ✧ Access points could be mounted on ceilings, walls, doorways, vehicles
- ✧ Massive Gbps data transfer while moving through a small area

Practical Opportunities

Automotive and the medicine industry plays a more and more important role for this kind of development

Automotive radar: 77 GHz

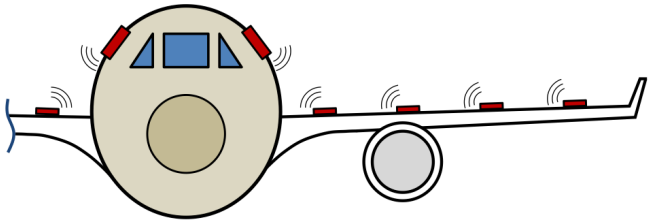


Intra vehicle communication:

- Inability to penetrate and interfere with other vehicle networks

In-flight Entertainment:

- Do not interfere with other aircraft communications



Satellite communication:

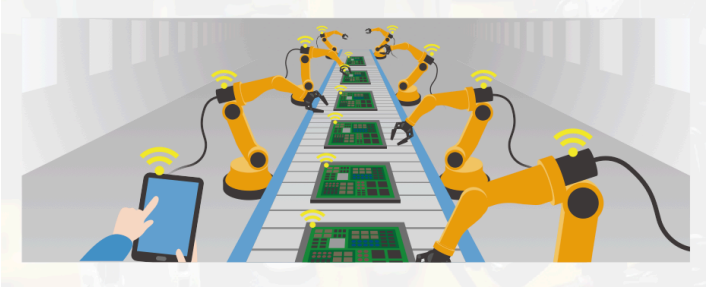
- Outside atmosphere
  - No free space path loss
  - Line-Of-Sight

Internet of Things and 5G

Internet of Things/5G

Key drivers very Briefly summarized: mmwave band the frequency

- Mobile video traffic increases rapidly:
  - Virtual realilty
    - Virtual games, live sporting events, remote presentation…etc.
- Smart driving:
  - Internet of Vehicles
    - Reduce traffic accidents, save energy and reduce pollution
- Smart Manufacturing:
  - Industry revolution 4.0
  - Complete manufacturing chain connected
  - Production efficiency will drastically improve



- Health:
  - Latency – Remote surgery is very latency intolerant

Large bandwidth and low latency are required for real time, high quality image processing and spatial location. More than 20 Billion devices expected to connected by 2020.

The **FUTURE** of connectivity

is

WIRELESS

In that context is the HEP community

not

an exception

Fundamental Data Capacity

Shannon's Theorem

Shannon's theorem gives an upper bound to the capacity of a link, in bps, as a function of the available bandwidth and the SNR

$$C = B \cdot \log_2\left(1 + \frac{S}{N}\right)$$

C = Channel capacity in b/s
B = Bandwidth in Hz
S = Signal in Watts
N = Noise power in watts

Increase data rate:

- ✧ Spectral Efficiency
  - Complexity, Power consumption
- ✧ Bandwidth (B)
- ✧ Signal-to-Noise-Ratio (SNR)

High Bandwidth:

Spectral efficiency not a dominant factor

Can trade bandwidth for complexity

Applications in HEP

ATLAS Silicon Micro-strip Tracker upgrade would require:

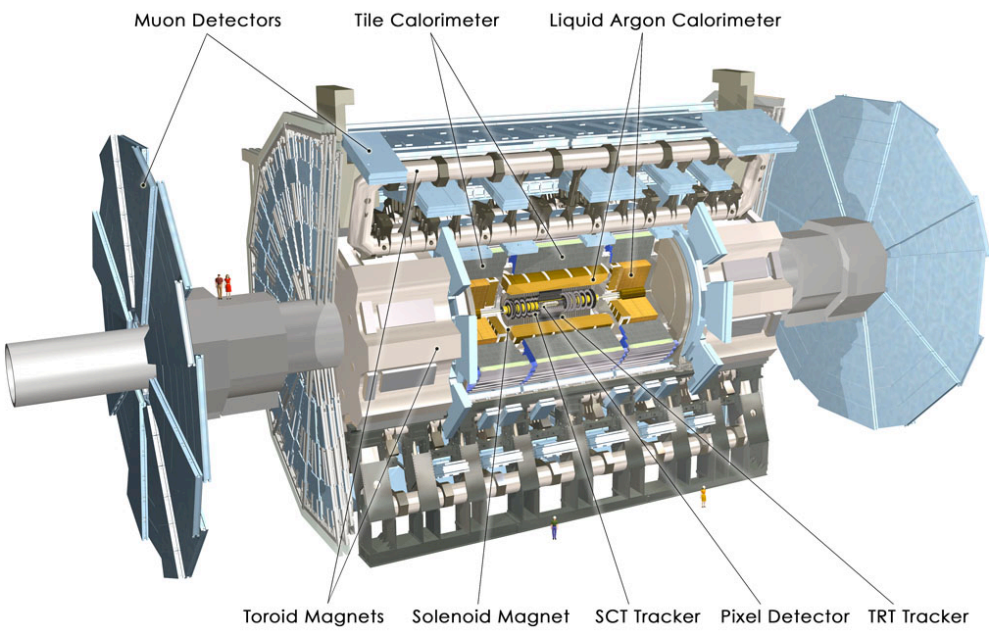
- ✧ Bandwidth of 100 Tb/s
- ✧ 20 000 links at 5 Gb/s

without increasing the

- ✧ Material budget
- ✧ Power consumption
- ✧ Space for services

and in addition

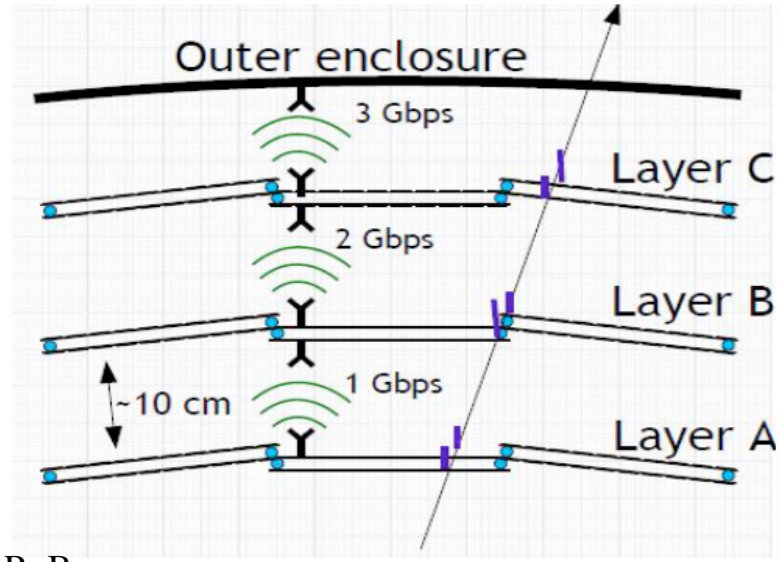
- ✧ Contribute to the fast trigger decision



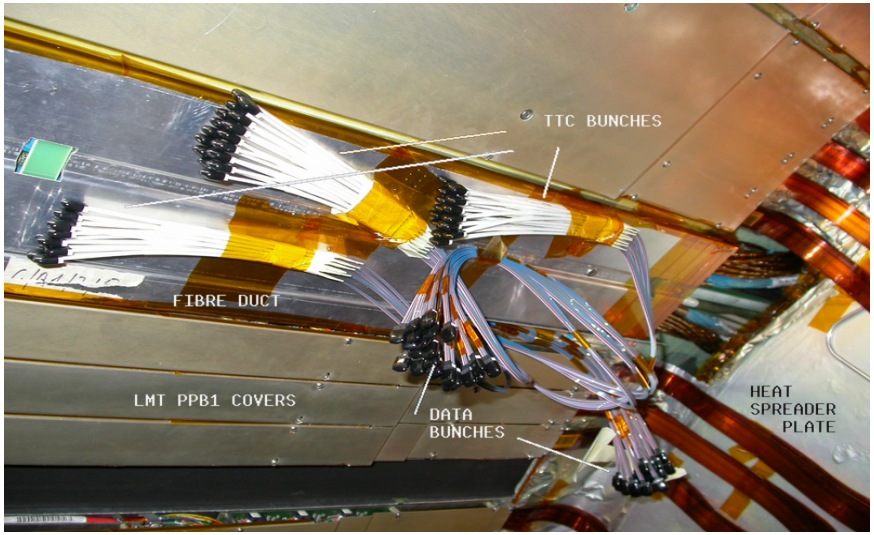
Applications in HEP

- ✧ Today the data are readout perpendicular to the particle path.
- ✧ Static system with Line-of-Sight (LOS) data transfer communication
- ✧ Approach: Readout radially by sending the data through the layer(s) by wire/via connection, with an antenna on both sides.

Reduce Material Budget
Less cables and connectors



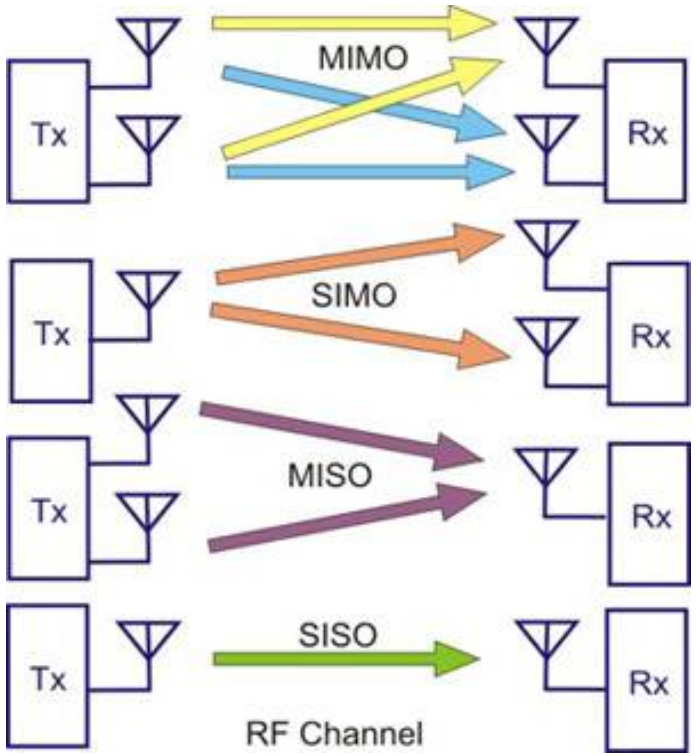
R. Brenner



Application in HEP

Steering and control of complex detector systems

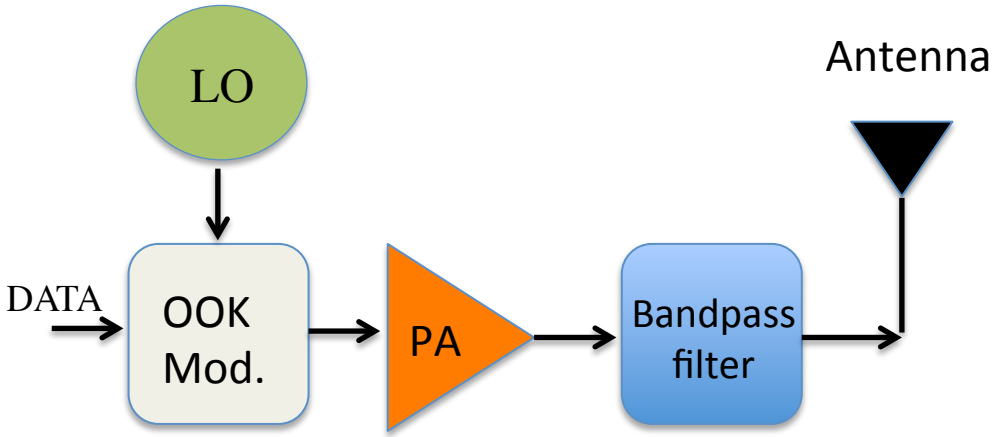
Create topologies which are much more challenging to be realized by using wires



- MIMO uses multiple antennas to transmit multiple parallel signals
- Data from one single transmitter can be sent to several receivers.
- Data from several transmitters send to one receiver
- Data from single transmitter to single receiver

This can totally or even partially remove cables and connectors that will/can result in cost reduction, simplified installation, repair and reduction in detector dead material.

Heidelberg ASIC

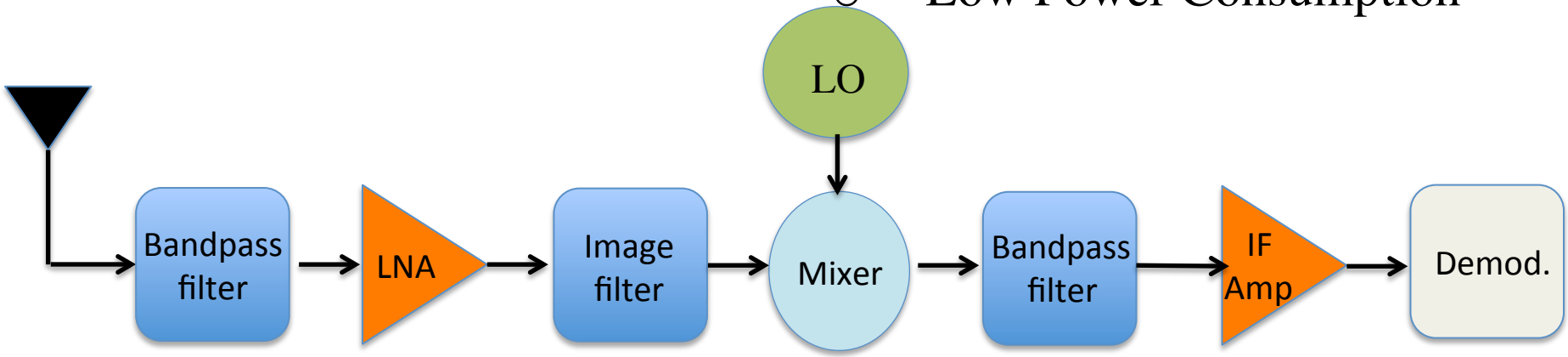


Transmitter:

- Deliver required output power
- Power efficient
- High gain and stability

Receiver:

- Balance gain, linearity and NF
- Low Power Consumption



System Specifications

System SNR_{min} is determined by the Bit-Error-Rate (BER) of a given Modulation scheme.

For OOK: $BER = 10^{-12} \rightarrow SNR_{min} \approx 17dB$

$$Noisefloor = -174dBm + 10\log_{10}(9G) = -75\ dBm$$

NF_{tot} chosen to be 9 dB

$$S_{RX} = Noisefloor + SNR_{min} + NF_{tot} = -49\ dBm$$

Minimum power level that the system can detect producing an acceptable signal SNR at the output.

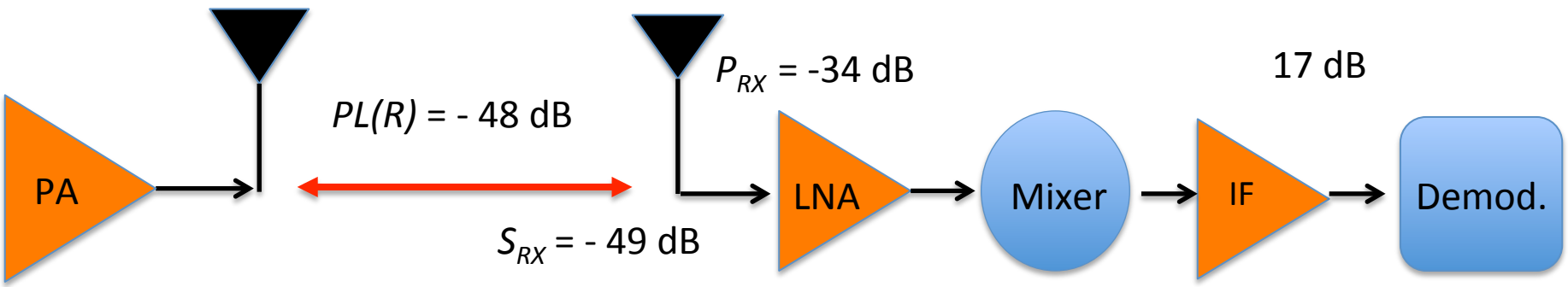
Specifications	Value
Frequency band	57-66 GHz
Bandwidth	**9 GHz**
Data Rate	**4.5 Gbps**
Modulation	OOK
Minimum sensitivity $S_{rx(min)}$	- 49 dBm
Bit Error Rate (BER)	10^{-12}
Target Power consumption	**150 mW**
Transmission Range	20 cm (1m)

Link-Budget

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{TX} - PL(R) - L_{RX} - FM$$

P_{RX} = RX Power (dBm)
P_{TX} = TX Power (5 dBm)
G_{TX} = Transmitter antenna gain (10 dBi)
G_{RX} = Receiver antenna gain (10 dBi)
L_{TX} = Transmitter losses (4 dB)
L_{RX} = Receiver losses (4 dB)
FM = Fading Margin (3 dBm)
PL(R) = Free space loss@20 cm(1m)= 48 (68 dB)

System operating margin: 15 dB



Technology

- 130 nm SiGe-Bi-CMOS
- SiGe NPNs, We = 120 nm, ft = 200 GHz, BVceo = 1.8V
- 130 nm CMOS FETs 1.5/2.5V

High Integration level

- Fully-characterized millimeter Wave Passive Elements
  - Resistors, Varactors, MOS, MIM-caps, inductors, Transmissions lines, etc.

- Silicon On Insulator (SOI)
  - Isolation in the gigahertz range

Compared to CMOS:
- Higher gm
- Lower 1/f noise
- Superior matching

For future developments:

Final choice of technology is still under discussion until final specifications are given

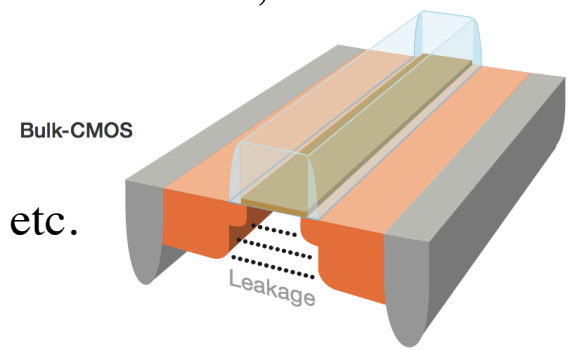
Technology Trends

Planar bulk CMOS reaching its limit at 20 nm:

- Technical challenges (leakage, variability and short channel effects)
- Cost efficiency challenges

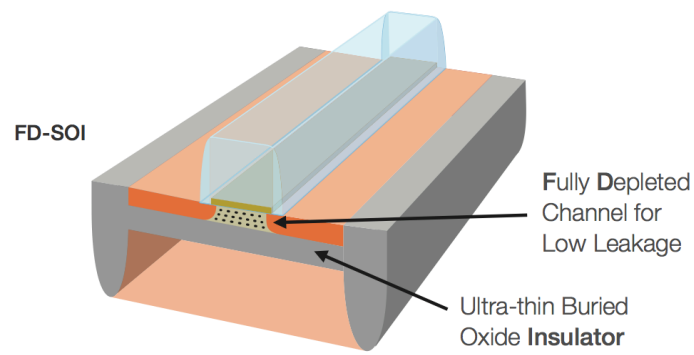
Dependent on where in the detector you place the RF electronic, it will have different requirements and specifications. Where are:

- Radiation hard design mandatory
- Data rate
- Analog performance, dynamic range, power consump. etc.



Challenges:

- Different architecture and choice of technology



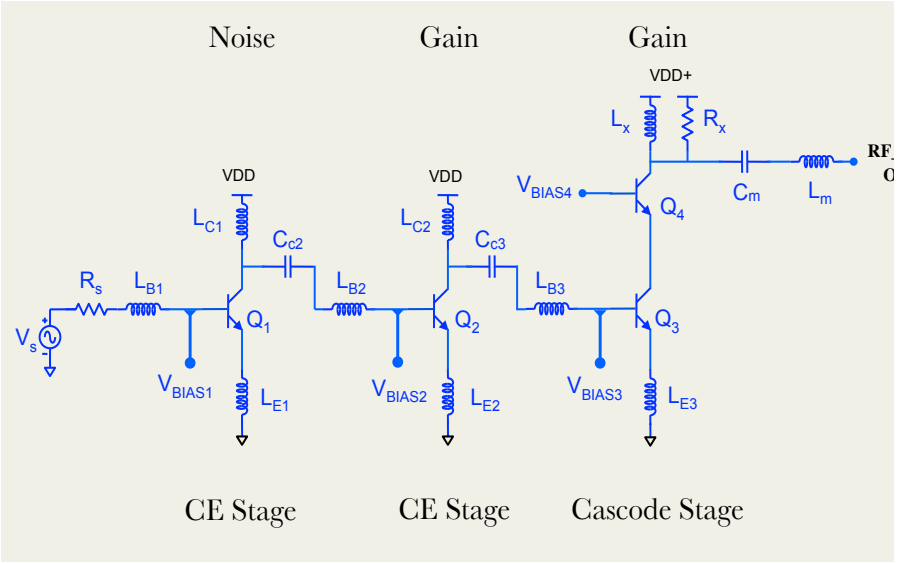
Four technology choices for mmwave

- SiGe BiCMOS (130 – 90 nm)
- RF CMOS (65 – 28 nm)
- PD-SOI (65 – 45nm)
- FD-SOI (65 -12nm)

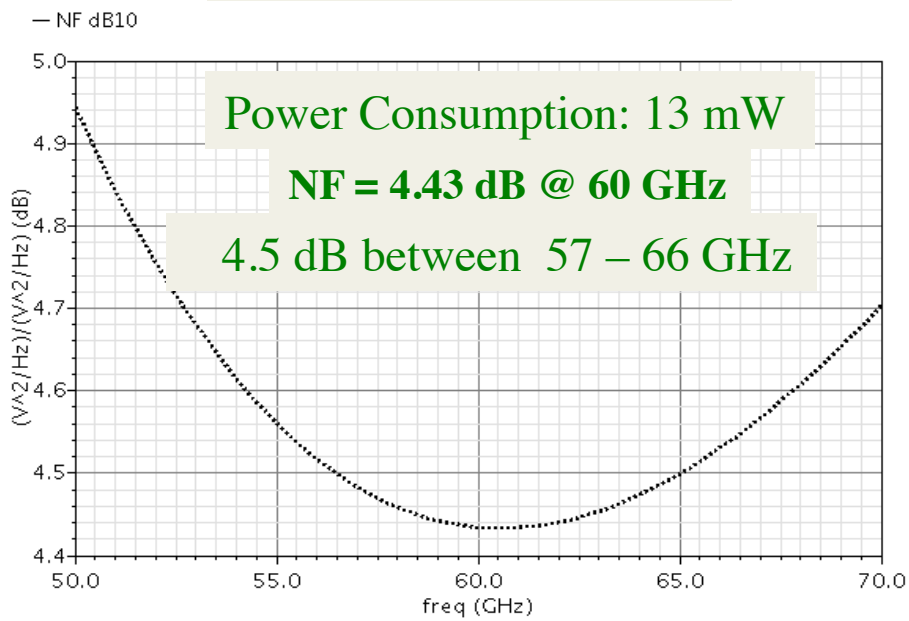
Simulations (LNA)

- Sets the lower limit of the system
- Optimized for NF and Gain

$$NF_{IN} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \frac{NF_4 - 1}{G_1 G_2 G_3} + \ldots + \frac{NF_n - 1}{G_1 G_2 \ldots G_{n-1}}$$



S-Parameter Response
Noise figure (NF)



Power Consumption: 13 mW

NF = 4.43 dB @ 60 GHz

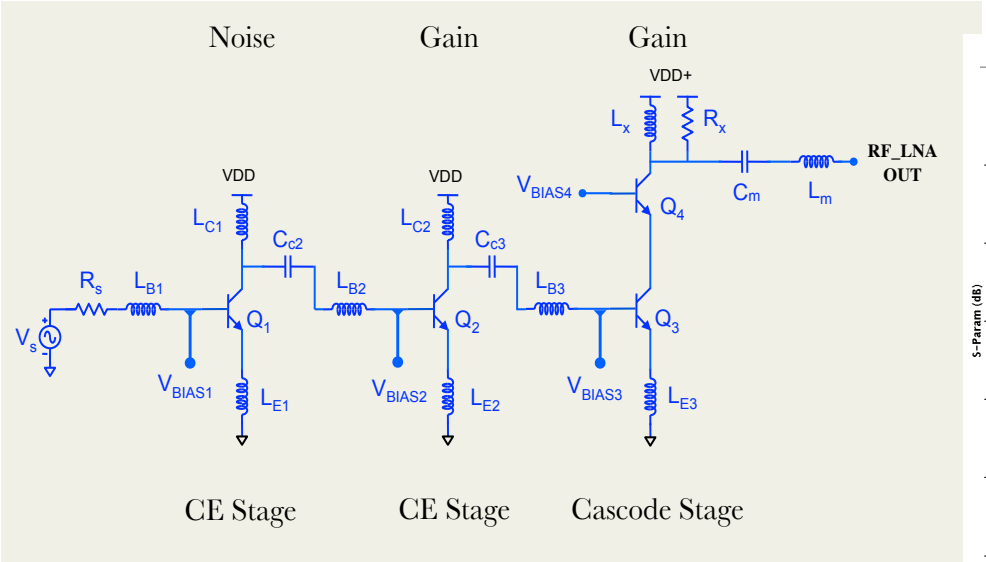
4.5 dB between 57 – 66 GHz

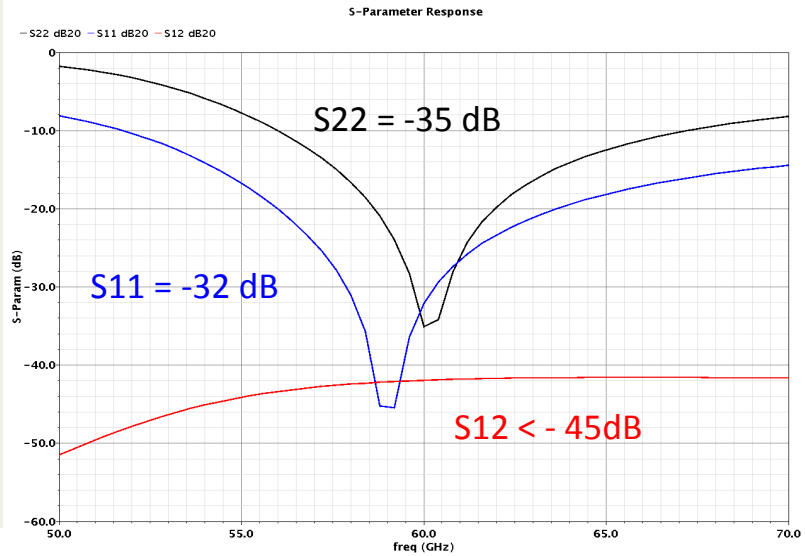
Simulations (LNA)

S-Parameter Response all @ 60 GHz

$$NF_{IN} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \frac{NF_4 - 1}{G_1 G_2 G_3} + \ldots + \frac{NF_n - 1}{G_1 G_2 \ldots G_{n-1}}$$

S11 - Forward reflection (input match)
S22 – Reverse reflection (output match)
S12 - Reverse Transmission (leakage)



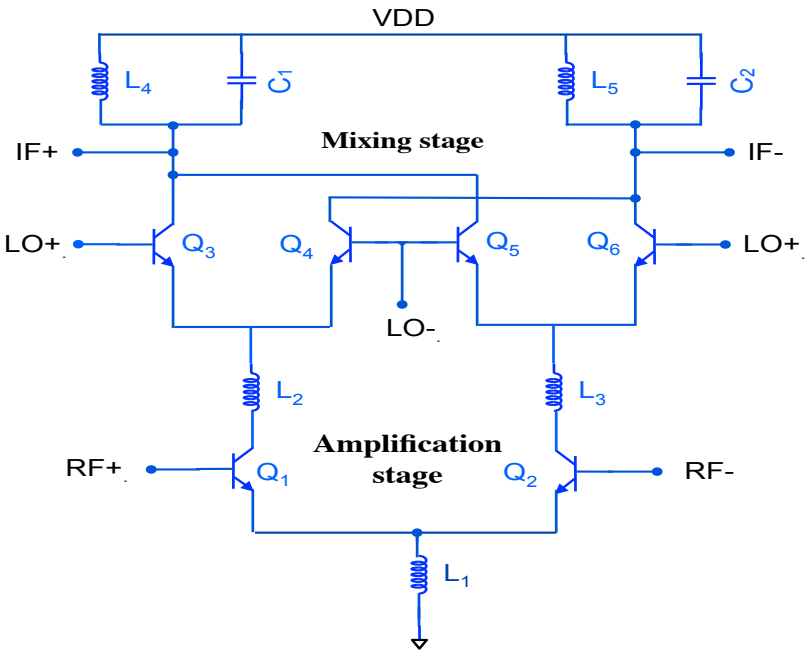


Gilbert Mixer

Translate an RF frequency to both a higher and lower intermediate frequency (IF)

The RF and LO frequencies are spaced apart by an amount equal to the IF frequency.

- ✧ Very good Isolation
- ✧ Harmonic suppression
- ✧ Noise Figure
- ✧ Immune to Port Feed-through
- ✧ Differential structure
- ✧ Integrated on-chip

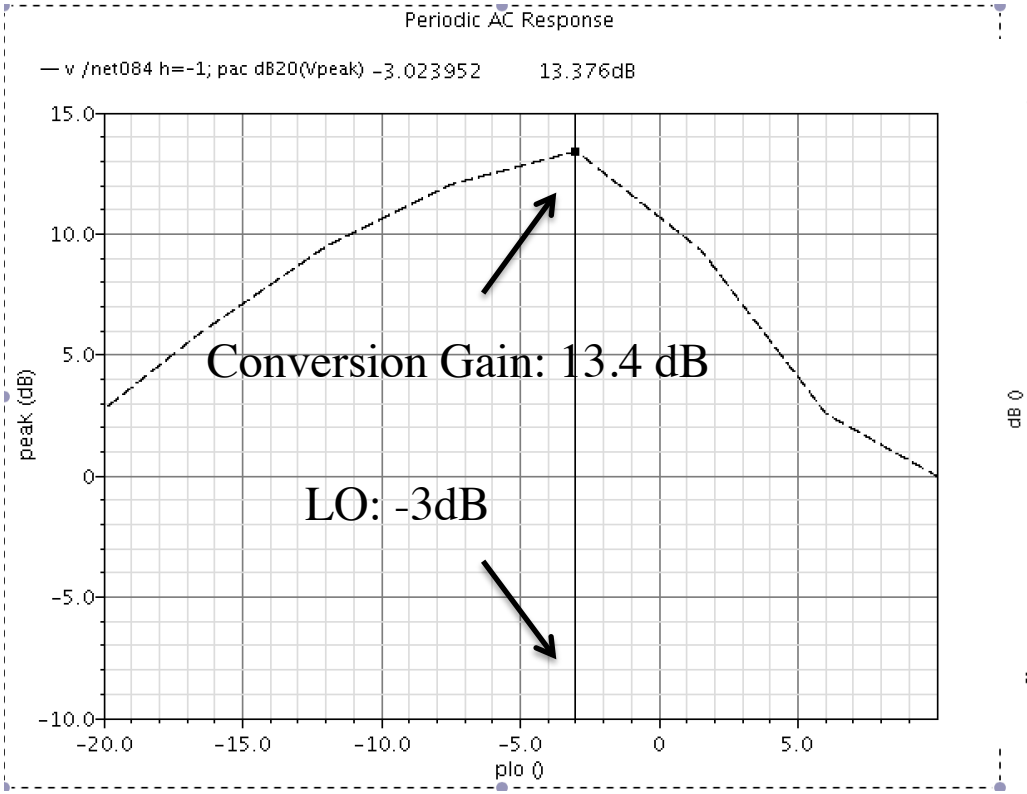


Linearity is also an issue since it must handle amplified signals

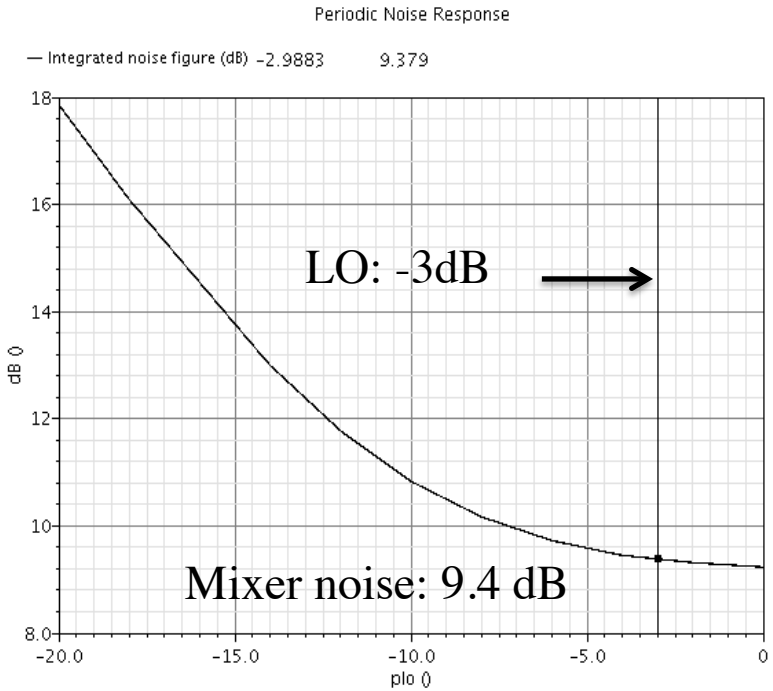
Gilbert Mixer

Power consumption: 7 mW

Conversion Gain

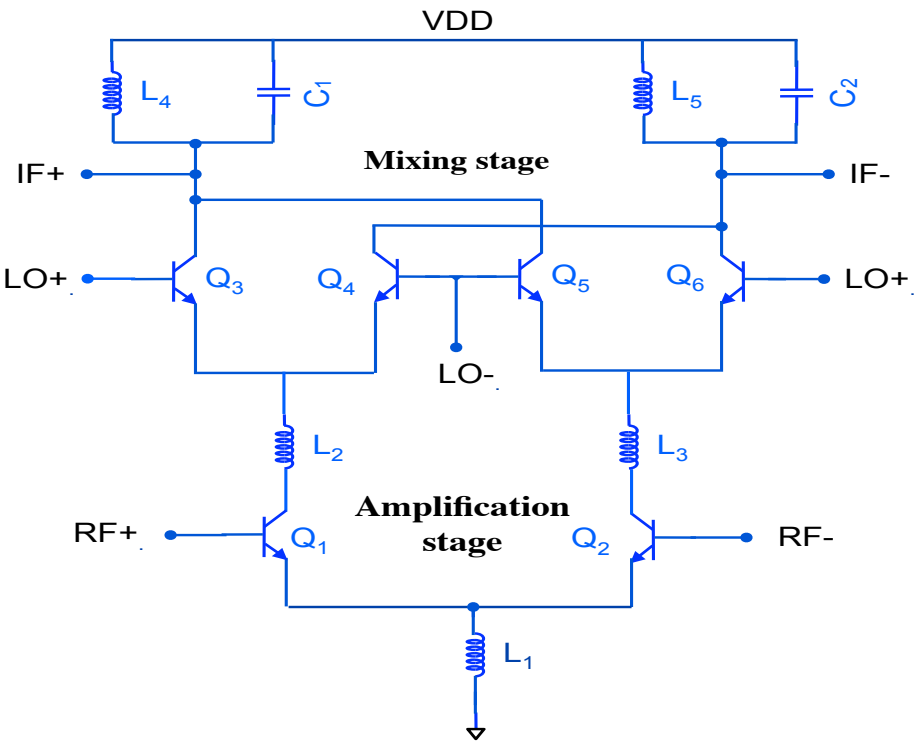


Mixer Noise



Gilbert Mixer

Mixer parasitic RF connection: Port-to-Port Isolation



Simulated values:

- RF-L0: -150 dB
- RF-IF: - 90 dB
- LO-IF: -100 dB
- LO-RF: - 82 dB

Why Modulation?

The basic principle of pass-band modulation is to encode information into a carrier signal (60 GHz) suitable for transmission

Motivation:

Simplify radiation of the signal

- Couple EM into space – antenna size a function of wavelength

$$\lambda = \frac{c}{f} = \frac{3.0 * 10^8}{60 * 10^9} = 5mm \qquad \lambda = \frac{c_0}{f\sqrt{\varepsilon_r}} \text{ (dielectric)}$$

- Frequency assignment:
  Allows multiple radio channels to broadcast simultaneously at different carrier or translate different frequencies to different spectral locations.

Factors influencing choice of Modulation

- ✧ Spectral efficiency
  - How effectively the allocated bandwidth is used (B/s/Hz)
- ✧ Bit Error Rate (BER)
- ✧ Signal-to-Noise Ratio (SNR)
- ✧ Power Efficiency
  - The power efficiency expresses the " signal energy over the noise energy" ratio (Eb/No) required at the receiver to guaranty a certain BER
- ✧ Performance in multipath environment
  - Envelope fluctuations and channel non-linearity
- ✧ Implementation cost and complexity

No modulation scheme possess all the above characteristics, so trade-offs are made when selecting modulation/demodulation schemes.

Modulation Schemes

Several modulation techniques are available, most of them fall into one of following categories :

1. Spectral efficiency
2. Cost efficiency
3. System complexity
4. Power efficiency

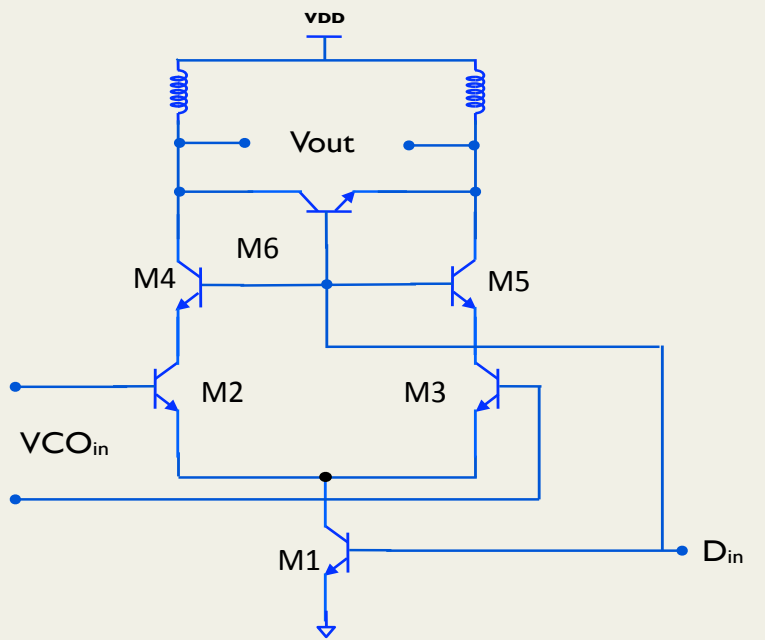
Modulation scheme	Modulation circuit Complexity	Demodulation circuit Complexity	IF Circuitry Complexity	Clock Recovery	Spectral efficiency B/s/Hz
OOK	Low	Lowest	Lowest	No	0.5
FSK (Coherent)	Medium	High	Lowest	Yes	1
MSK	High	High	Low	Yes	1
OFDM	Highest	Highest	Low	Yes	3

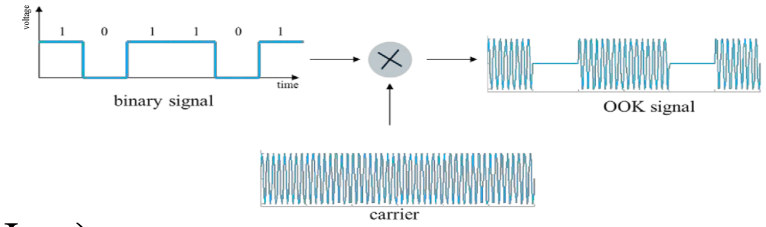
On-Off keying Modulation

- ✧ Spectral efficiency: 0.5 bps/Hz
- ✧ Sensitive to noise and interference
  - Mitigated by proper shielding and use of directive antennas

But

- ✧ Non-coherent demodulation
- ✧ Simple implementation
- ✧ Use non-linear PA
- ✧ Little power consumption
  - Constant envelope (no Amplitude Var.)





Voltage Controlled Osc.

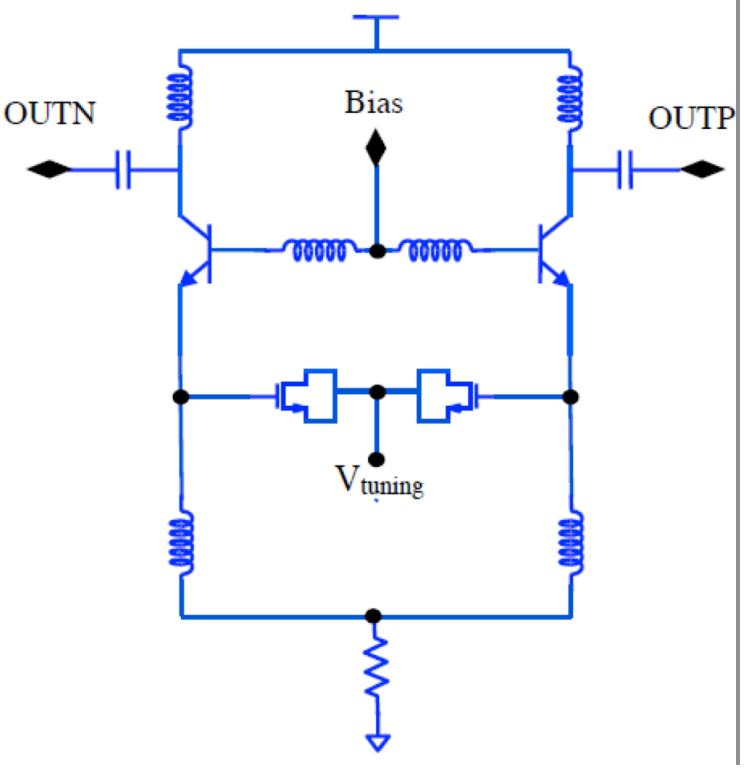
Used to provide the reference frequency to the modulate/ demodulate the RF signal

VCO design goals:

- Phase Noise: -90dBc/Hz@1MHz
- Tuning Sensitivity and Linearity: 57 – 66 GHz
- Output Power: -3 dBm
- Tuning range of 10%

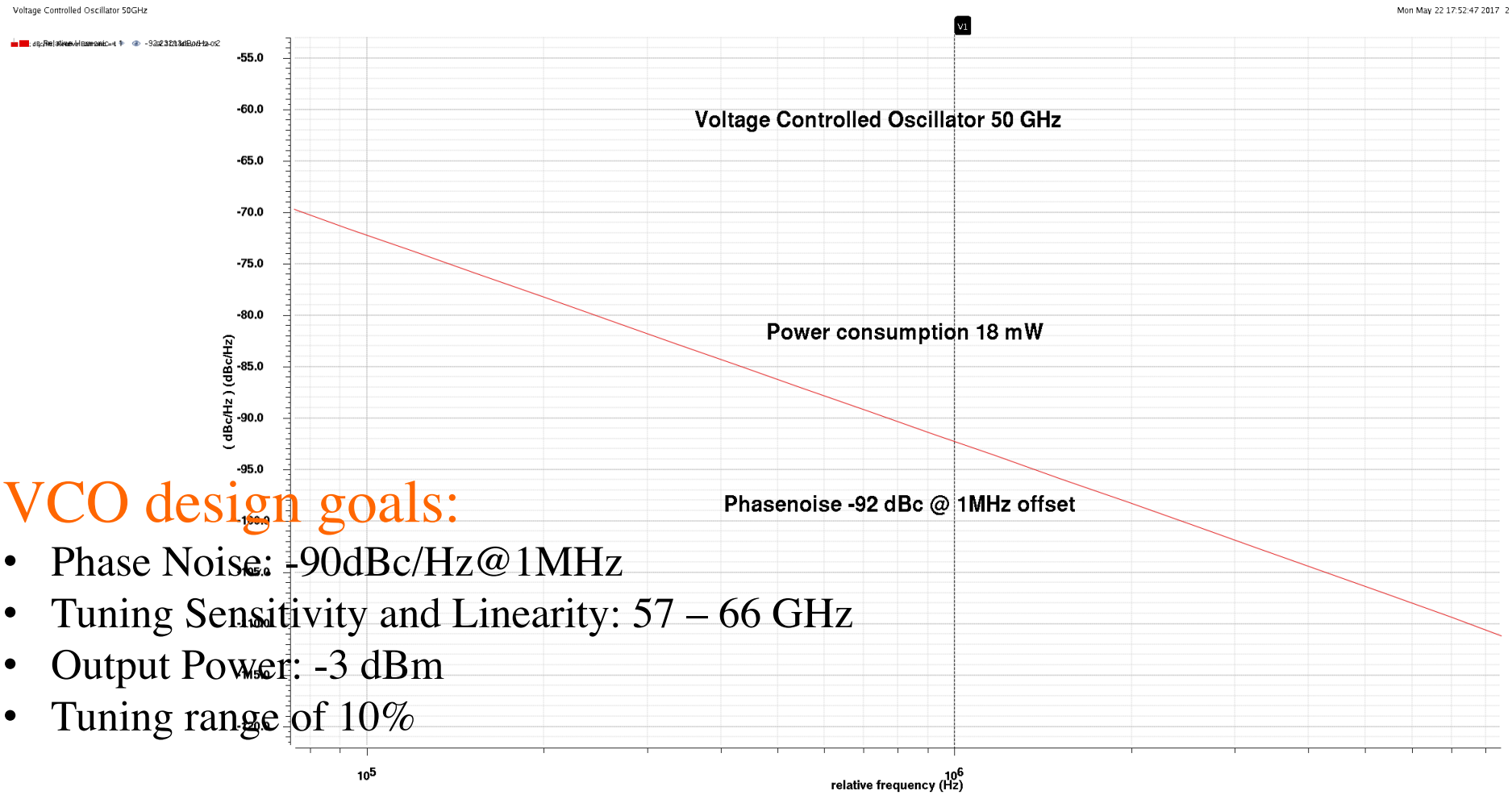
Colpitts topology chosen:

- Low Phase Noise
- High Frequency behavior
- Well proven differential topology
- Single transistor topology:
  - Reduce supply voltage, phase noise and layout
- Inductor used:
  - Reduce area, power and phase noise



Simplified version

Voltage Controlled Osc.



VCO design goals:

- Phase Noise: -90dBc/Hz@1MHz
- Tuning Sensitivity and Linearity: 57 – 66 GHz
- Output Power: -3 dBm
- Tuning range of 10%

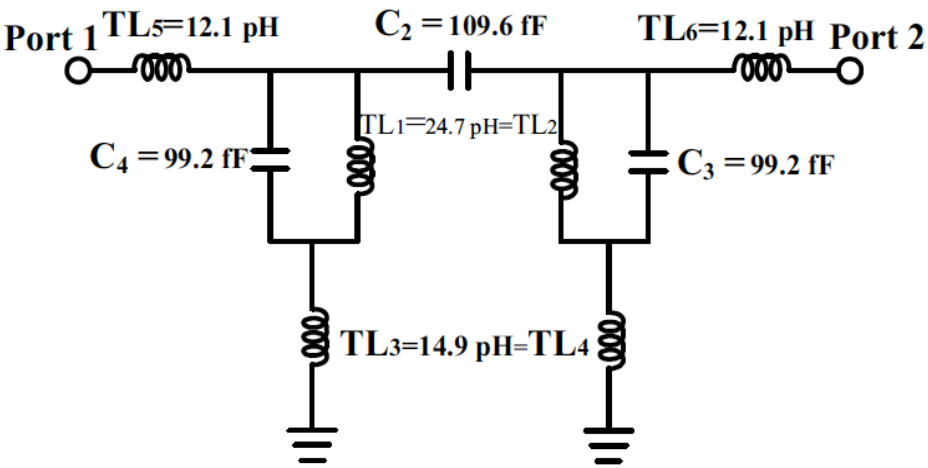
Filter Design

Important role in transmitters and receivers to remove out of band signal that otherwise would be modulated

Used as preselect, image-rejection and IF filter

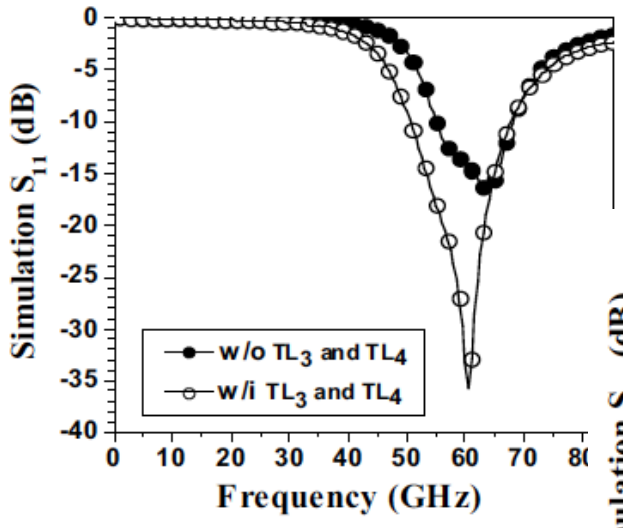
Design Parameters	Specifications
Center frequency	61 GHz
S11	≤ -10 dB
S22	≤ -10 dB
S21 (low loss)	~ -2 dB
Frequency range	57 – 66 GHz

Third-order Chebyshev bandpass filter

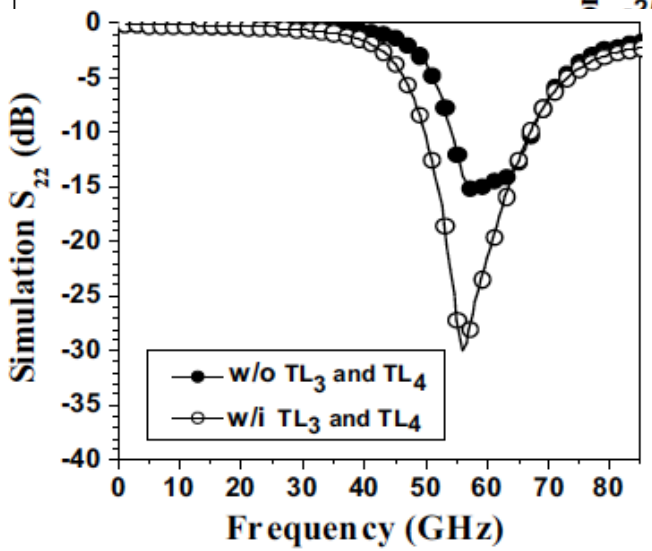


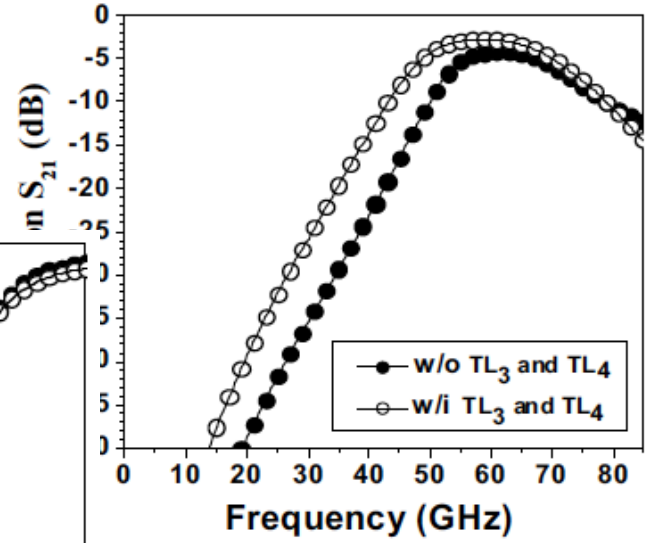
Mei-Chung Lu et al.
Miniature 60-GHz-Band Bandpass Filter with 2.55-dB Insertion loss Using standard 0.13 µm CMOS Technology.
VLSI Design, Automation and Test, 2009. VLSI-SAT'09. International Symposium on

Filter Design



S22 better than -10 dB
Over 53 -71 GHz





S11 better than -10 dB
over 53 – 72 GHz

S21 lower than -3 dB
over 57 -69 GHz

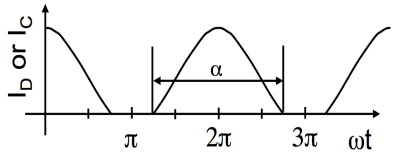
Implemented in standard p-type silicon substrate with thickness of 300 µm

Mei-Chung Lu et al.
Miniature 60-GHz-Band Bandpass Filter with 2.55-dB Insertion loss Using standard 0.13 µm CMOS Technology.
VLSI Design, Automation and Test, 2009. VLSI-SAT'09. International Symposium on

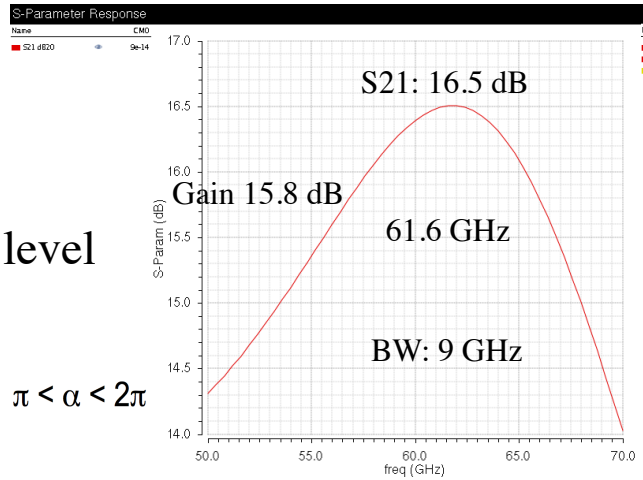
Simulations (PA)

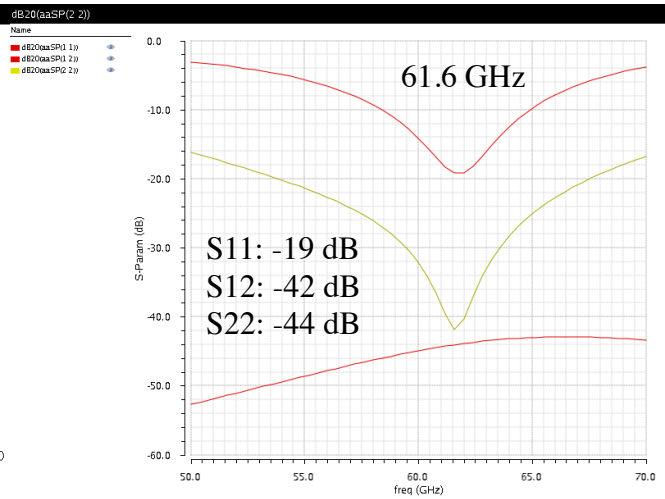
- Drives the antenna
- Isolation
- Power Added Efficiency
- Provide the required power level

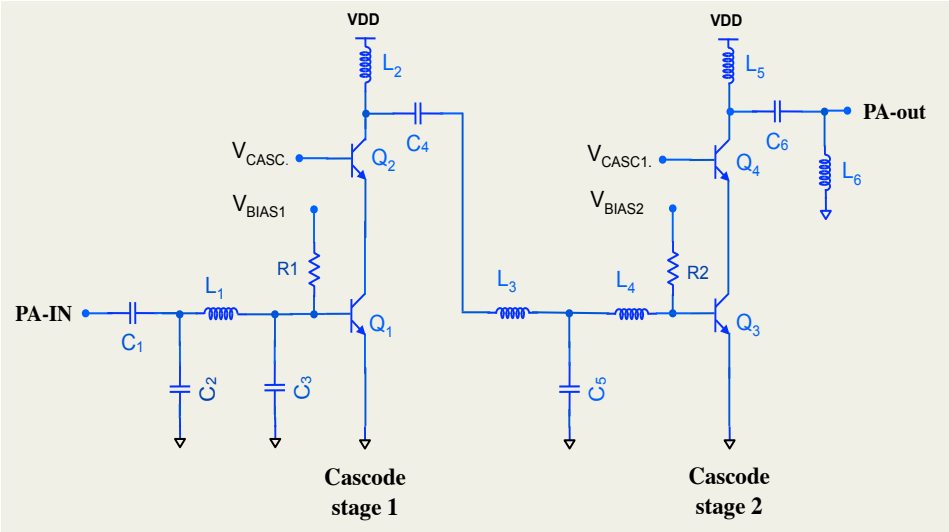
Class AB:



$\pi < \alpha < 2\pi$





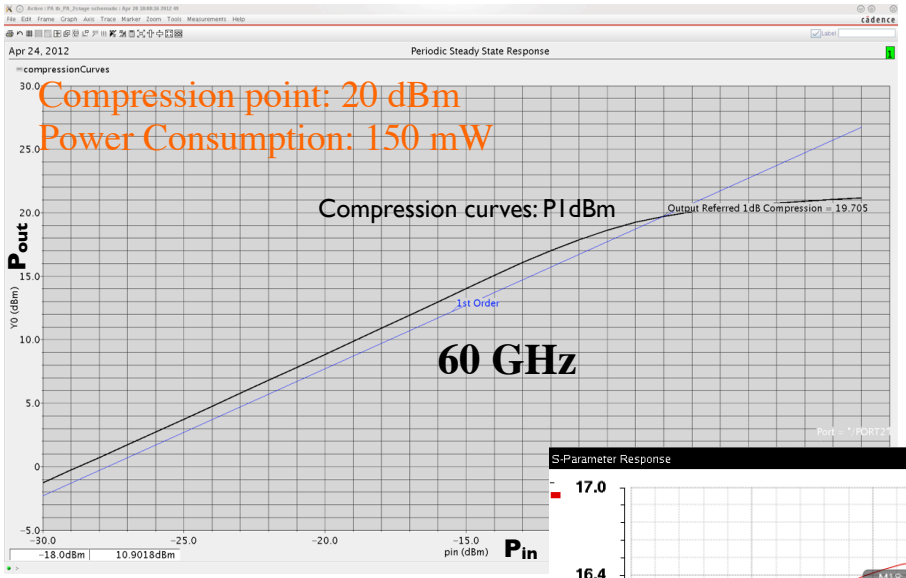


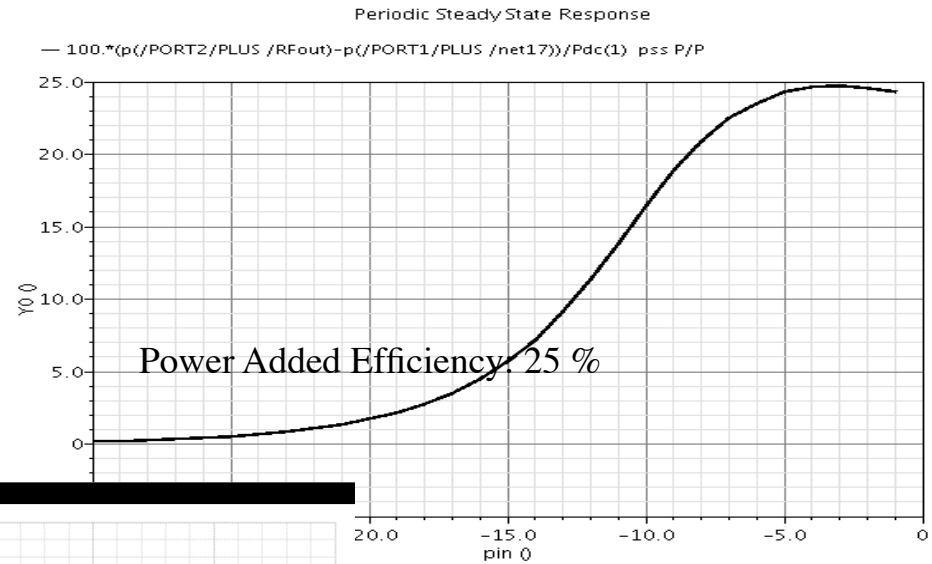
Peak Frequency: 61.6 GHz

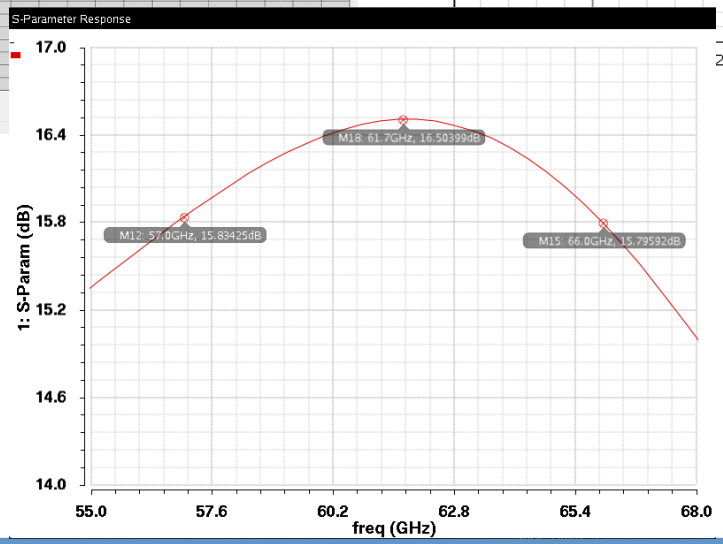
- ✓ S12 and S22 << -10 dB (57 – 66 GHz)
- ✓ S11 = - 8 dB
- ✓ S21 = 16.5 dB with +- 0.8 dB (57 -66 GHz)
- ✓ P1dB = 5 dBm
- ✓ Power consumption 60 mW

Simulations (PA)

High Power/long distance version







Preliminary Power Estimate

More blocks under development, to early show their characteristic behavior.

• Low Noise Amplifier:	13 mW
• Gilbert Mixer:	7 mW
• Local Oscillator:	20 mW
• Intermediate Amplifier:	10 mW
• Modulation Scheme:	20 mW
• Demodulation Scheme:	20 mW
• Power Amplifier:	60 mW

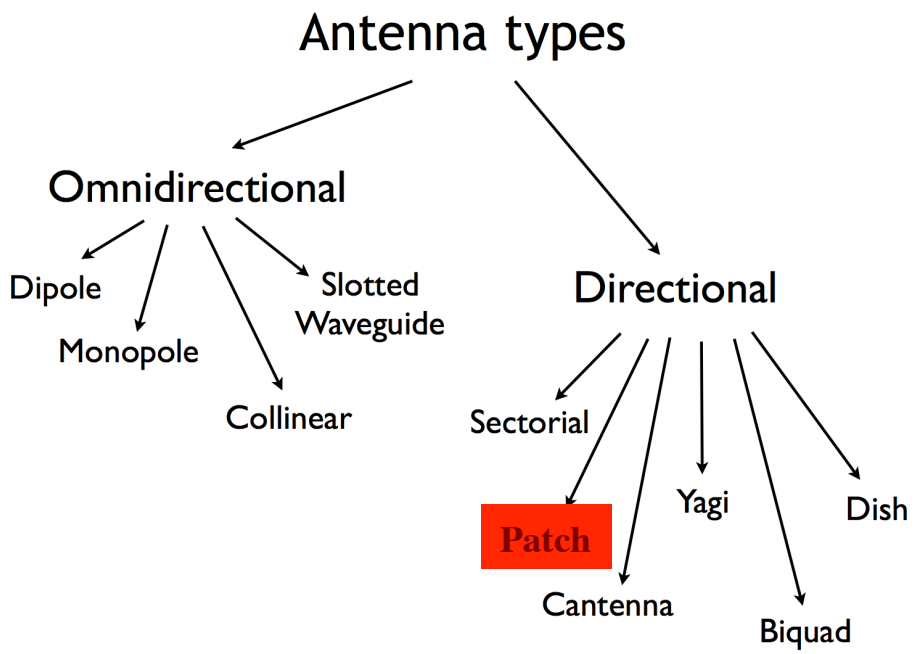
Power Consumption: 150 mW

Data rate:	4.5 Gbps
BER:	10^{-12}
Bandwidth:	9GHz
Distance:	20 cm - 1 m

Still room for Power Consumption optimization

Antenna Design

- ✧ Passive component and do not generate power
- ✧ Rely on antenna gain to close the link budget
- ✧ Largest part of the transceiver



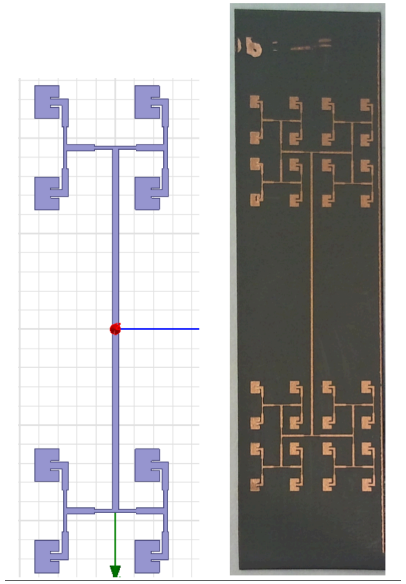
Antenna requirement:

- ✧ Light weight
- ✧ Compact
- ✧ Reproducibility
- ✧ Easy to fabricate
- ✧ Cost

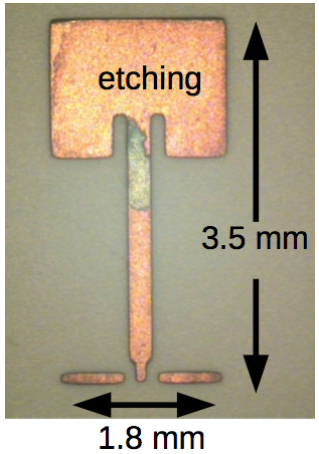
Antenna Design

Uppsala

Started to design and produce patch antennas

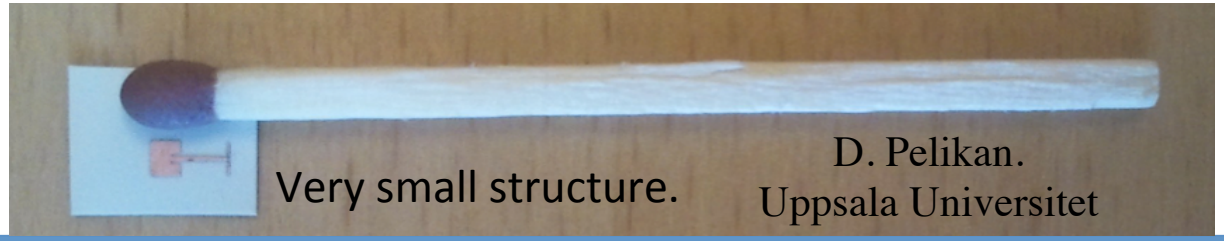


- Single and antenna arrays
- Can be produced on PCB material
  - Etching and milling.
  - Rogers, Dupont PCB material



1, 4 and 16 patch design

- Patches are connected by micro-strip transformations (Imp. Matching)
- Antenna arrays are connected by micro-strip

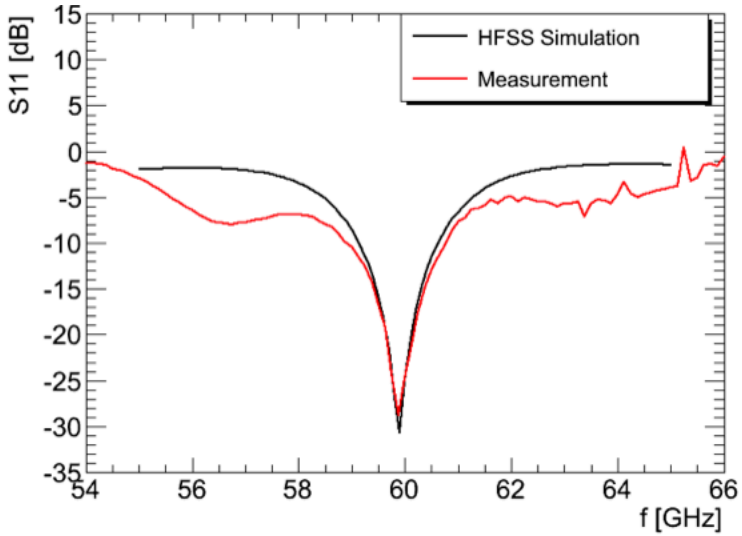


Antenna Simulation

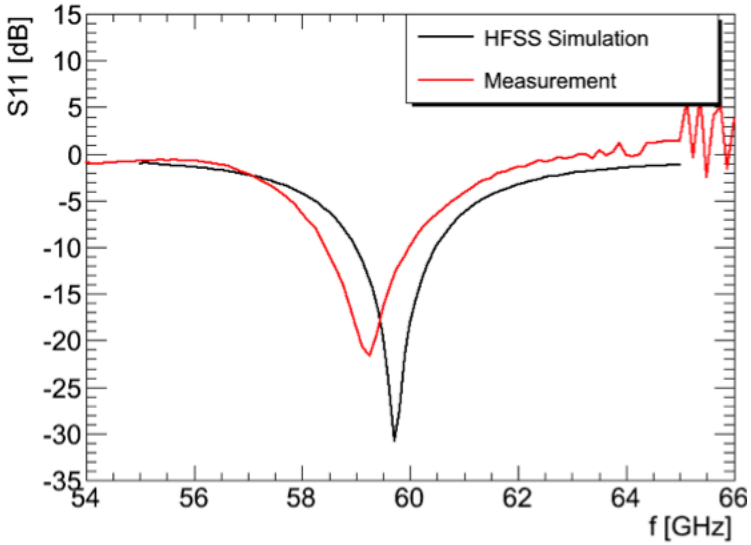
Etched antennas were used (PCB etching process)

4 Patch Antenna array: Very good agreement with simulation
1 Patch Antenna: A shift of 500 MHz seen

Good results: It shows that antenna production is possible



4 Patch design

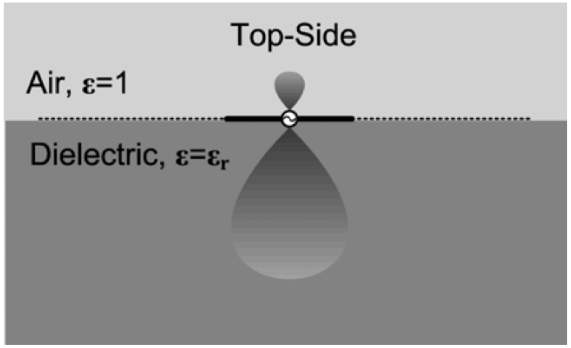


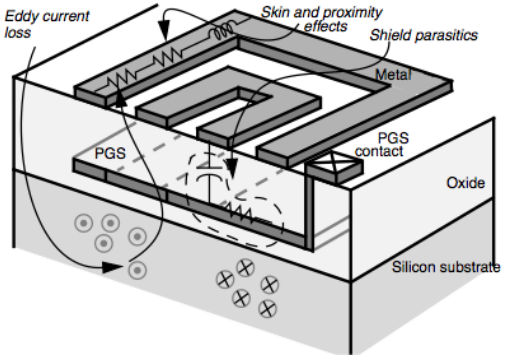
single patch design

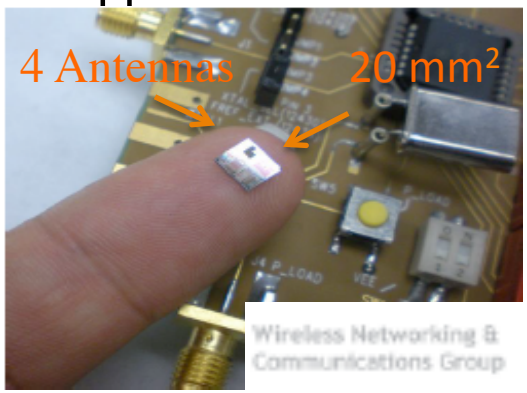
Antennas that cover a broader bandwidth 9 GHz is under development

On-chip Antenna

- Small wavelengths at 60 GHz (5mm $\lambda/4$=1.25 mm)
- Possible to integrate receive and transmit antenna(s) on chip.
- Multiple metal layers on ICs available
  - Can be used to fabricate mm-wave antennas.
- Eliminate cable/connectors loss and the need for ESD protection
- Cost effective compared to a packaged solution with off-chip antenna
- Issue: On-chip antenna in silicon has a very low radiation efficiency
  - High dielectric constant (11.7) and low substrate resistivity (10 Ohm-cm)
  - Energy loss due to magnetically induced current
  - Ohmic loss can be high, small skin depth (300nm) of copper at 60 GHz.







CEA Leti mmW developments

Chip	Standard	Range	Data rate	Power consumption	Maturity
Frequency domain 60GHz transceiver	802.11ad WiHD	0,5-2m	1-4Gbps	~400mW	prototype
Time domain 60GHz transceiver	No standard	5-20cm (2-5m with lens)	500Mbps-2 Gbps	~70-100mW	prototype
E-band Backhaul	No standard	100-200m with lens	1-8Gbps	NA	Some IPs

Time Domain 60GHz transceiver

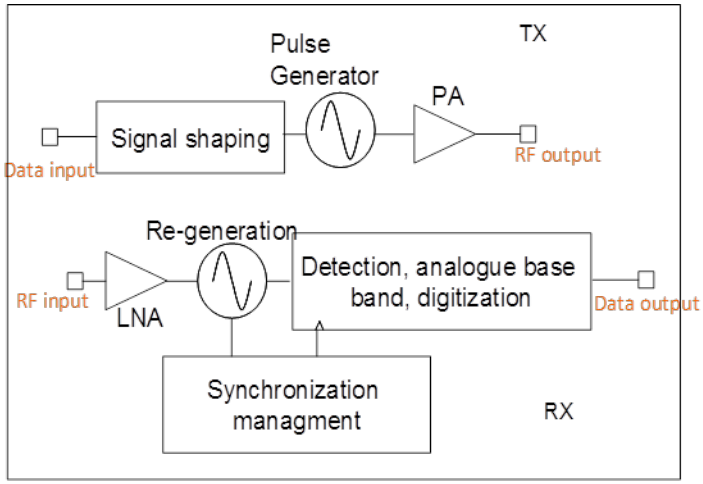
Power consumption @ 2.5Gbps (RFFE +DBB): TX 30mW, RX 70mW

Range 0.2m meter with single antenna

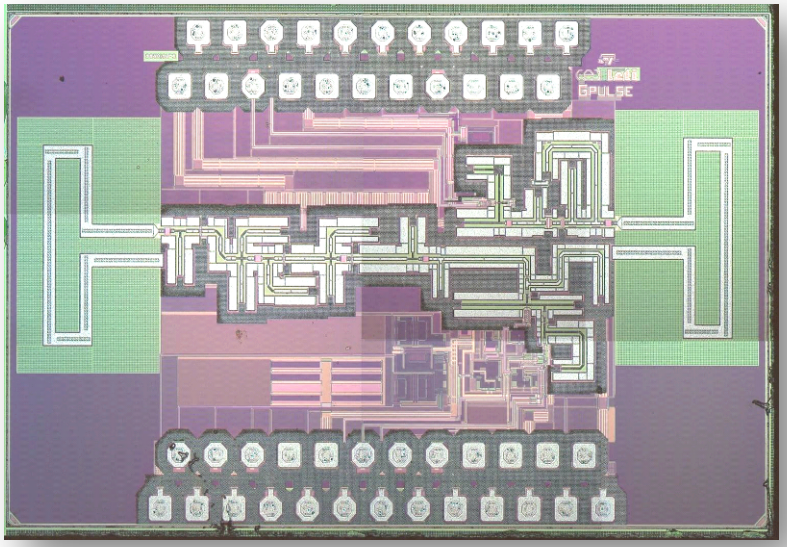
Scalable data rate from 100Mbps to 2.5Gbps

Integrated 4dBi 60GHz antenna (thanks to SOI 65nm HR process)

Very low cost (standard QFN package)



1,9mm x 3,1mm

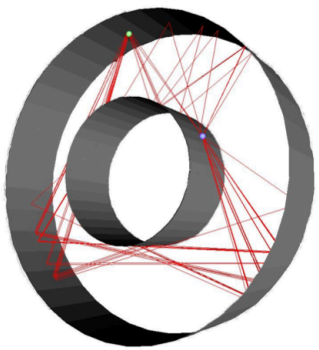


Feasibility studies
@
University of Heidelberg

S. Dittmeier, A. Schoening, H.K. Soltveit, D. Wiedner, Nucl.Instrum. Meth. A830 (2016) 417-426

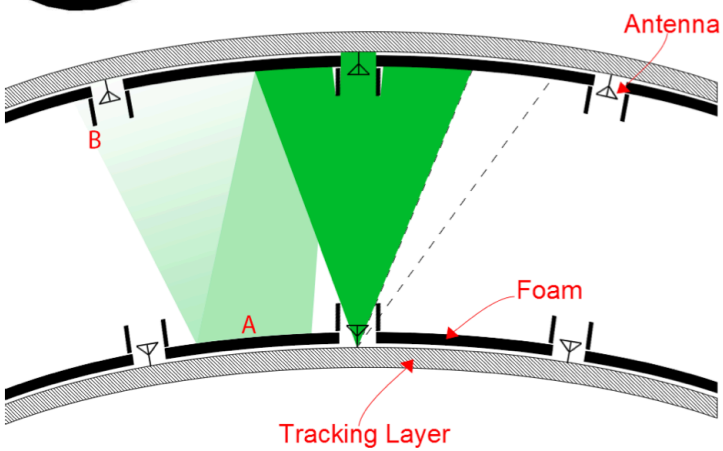
General questions

✧ Electromagnetic influence on the detector material



Simulations with a ray tracer have shown
(B.Sc. Thesis by Thomas Hugle)

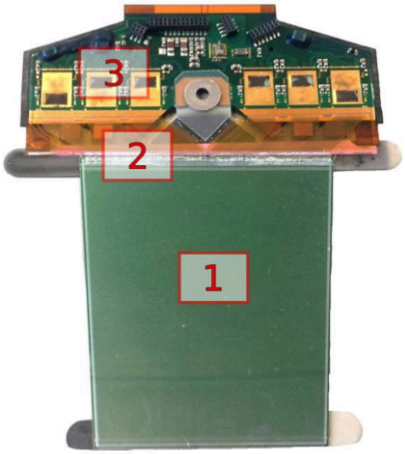
In a highly reflective environment, directing and / or shielding the signal is essential



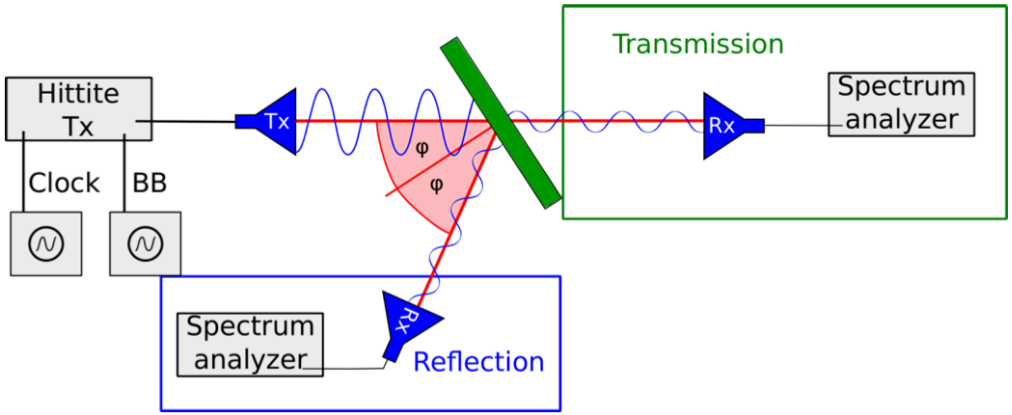
✧ How to avoid crosstalk?
- ✧ Absorption of reflections
- ✧ Directive antennas
- ✧ Linear polarization
- ✧ Frequency channeling

✧ Signal pickup:
- ✧ Detector electronics
- ✧ Transceiver

Electromagn. Properties



Unpowered spare ATLAS SCT end cap module w/o ABC-chips (provided by Uni Freiburg)



Tested Properties:

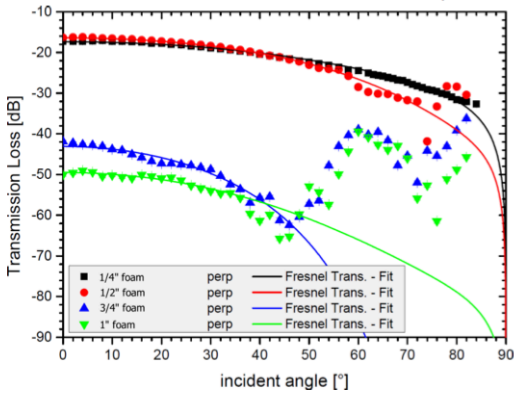
- Transmission loss
- Reflection loss

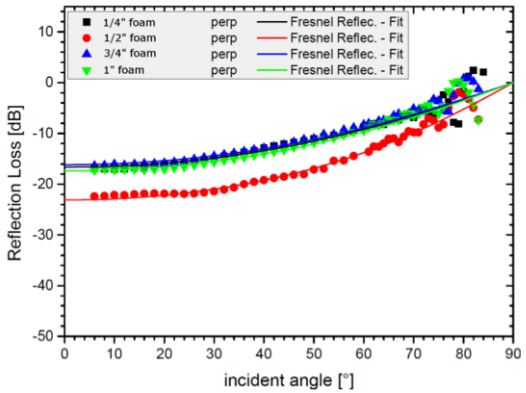
Tested homogeneity of transmission depending on

- Position
- Frequency

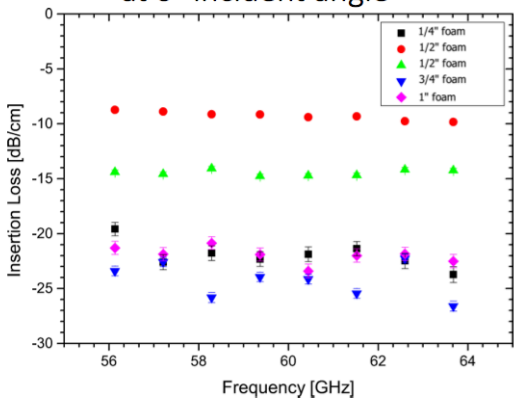
Graphite Foam

fixed frequency: f = 60.721 GHz

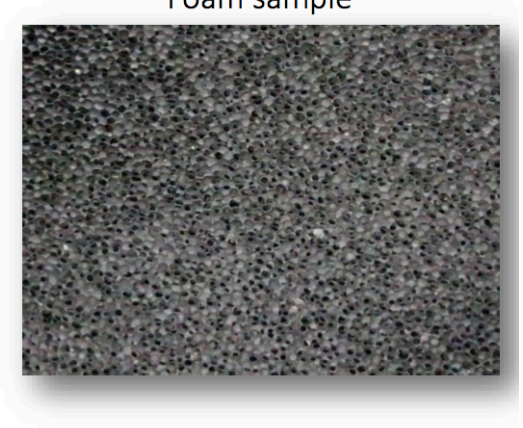




Frequency dependence
at 0° incident angle

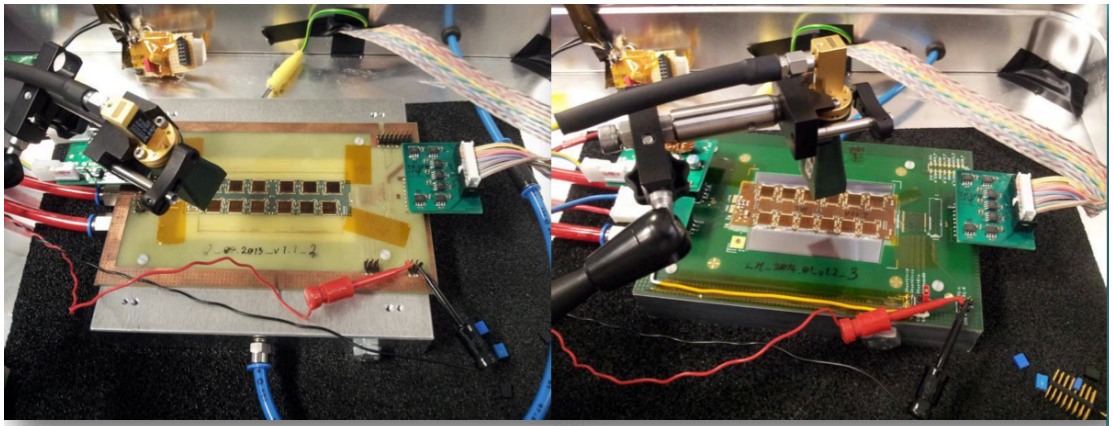


Foam sample

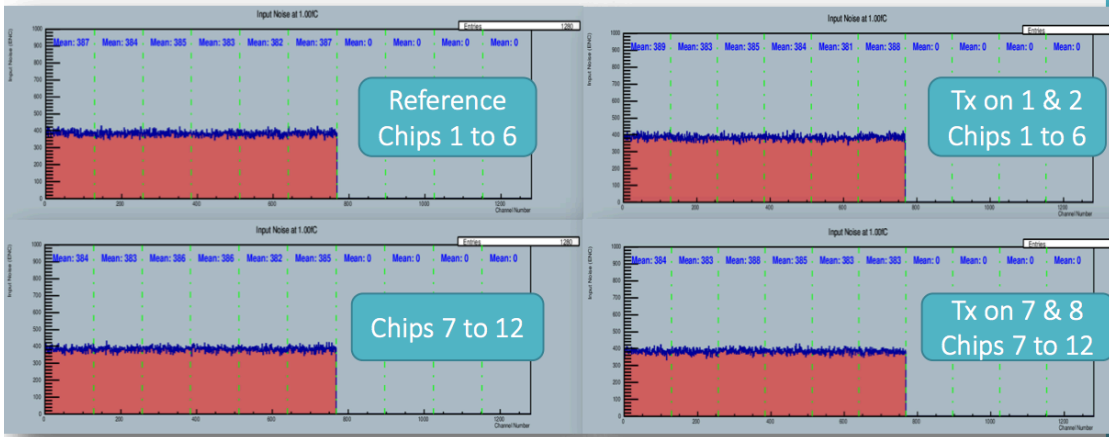


- ✓ Transmission reduced by > 15-20 dB
- ✓ Reflections reduced by > 10 dB up to large angles
- ✓ Absorption (20 dB/cm) to reduce transmitted intensity, stable over frequency
- ✓ Low density material: p = 50 – 70 mg/cm^3

Detector performance under 60 GHz "Irradiation"



Hybrid w/o silicon – no influence on chips (preliminary)



- ✧ Tests done using ABC-next Hybrid for the upgrade of ATLAS endcap detector

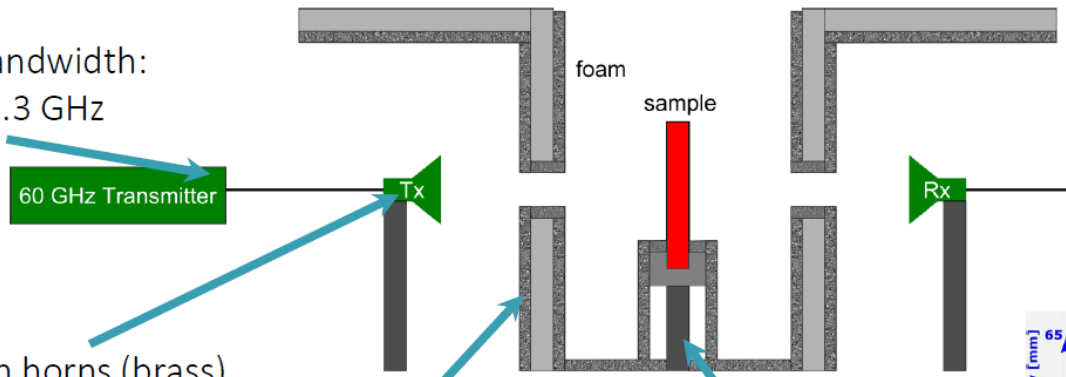
- ✓ No influence of noise was measured
- ✓ Performance of detector **<u>will not degrade</u>** by 60 GHz waves

Transmission:
SCT Barrel Module

Transmission through detector modules

Tested bandwidth:
57.3 – 61.3 GHz

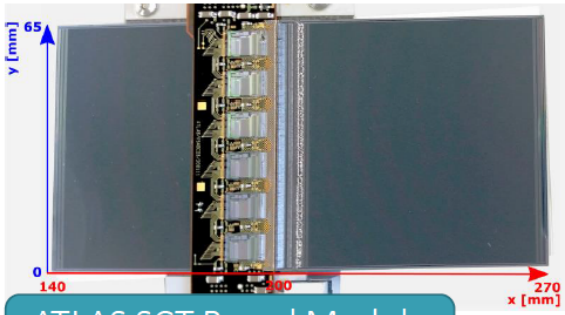
Measure power in RF
sensitivity of $\approx -55\text{dB}$
relative to transmitter



20 dBi gain horns (brass)
20 ° beamwidth
Linear polarization

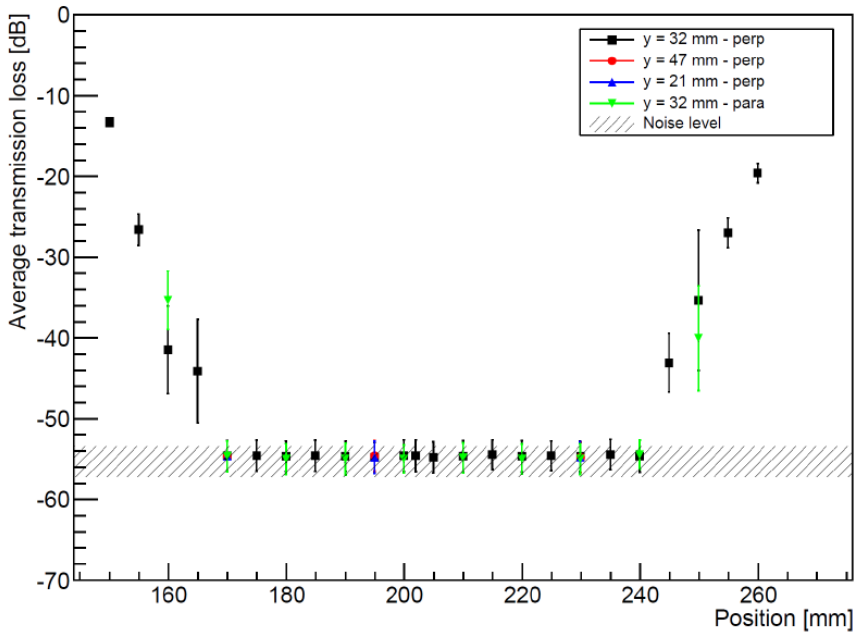
Aluminum and graphite
foam shielding against
reflections

Rail and post holder to
move sample



ATLAS SCT Barrel Module
R.Brenner (Uppsala)

Transmission:
SCT Barrel Module



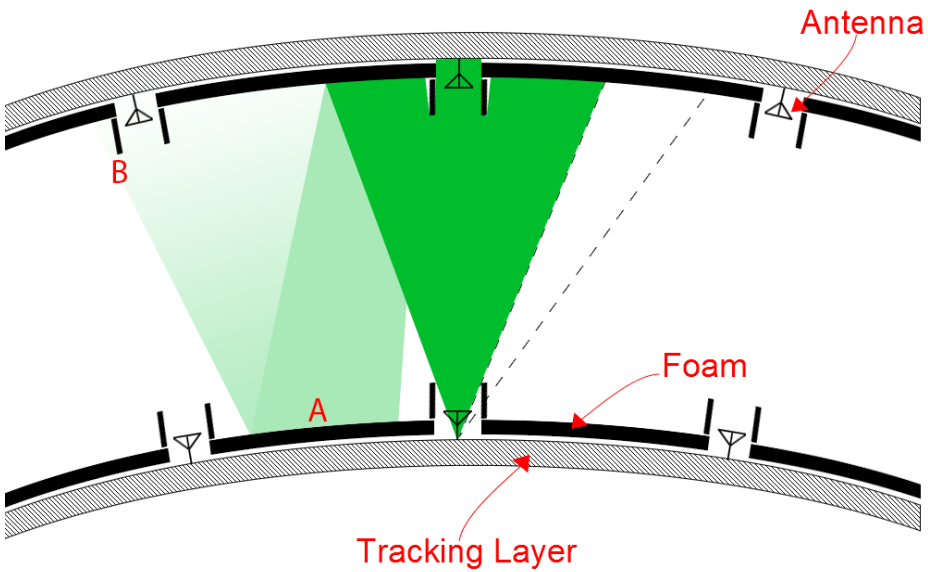
- Transmission Loss
  - $I_{loss} > 50$ dB
  - 60 GHz signals are fully reflected
  - Diffraction leads to transmission near edges.

Crosstalk

Ray tracing simulation: crosstalk mitigation

Approach:

- Directive horn antenna (25 dBi gain), polarization diversity
- Graphite foam absorbing material (loss: 15-20dB transmission, 10dB reflection)



Summary of feasibility studies

The tests has shown that the **Performance** of detector modules will **not** be degraded by 60 GHz waves.

- ✓ SCT detector modules attenuate transmission of 60 GHz waves by > 55 dB
- ✓ By means of antennas, polarization and graphite foam a high link density can be achieved. Link pitch < 5 cm@S/N > 20

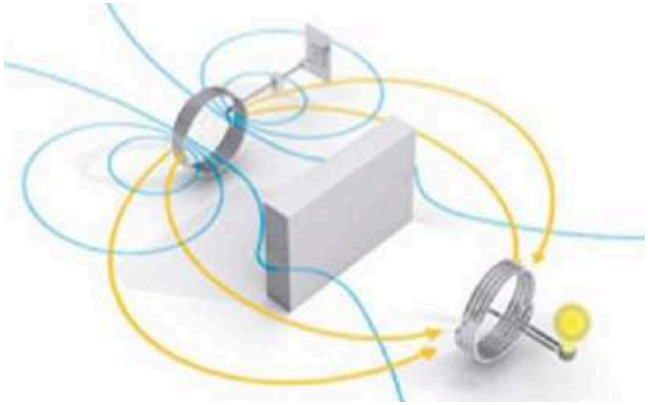
Combining these measures: Highly directive antennas, absorbers (graphite foam), linear polarization and frequency channeling, a data rate density of
3.7 Tb/(s*m^2) (Theoretical)

Wireless Electricity
(WITRICITY)

Wireless power transmission is needed where instantaneous or continuous energy transfer but interconnecting cables are inconvenient (limited space), dangerous or impossible

Magnetic resonant coupling:

Reduce cable pollution, such as cable number, material performance and power efficiency



- ✧ Medium range (room/detector size) 2-3 m

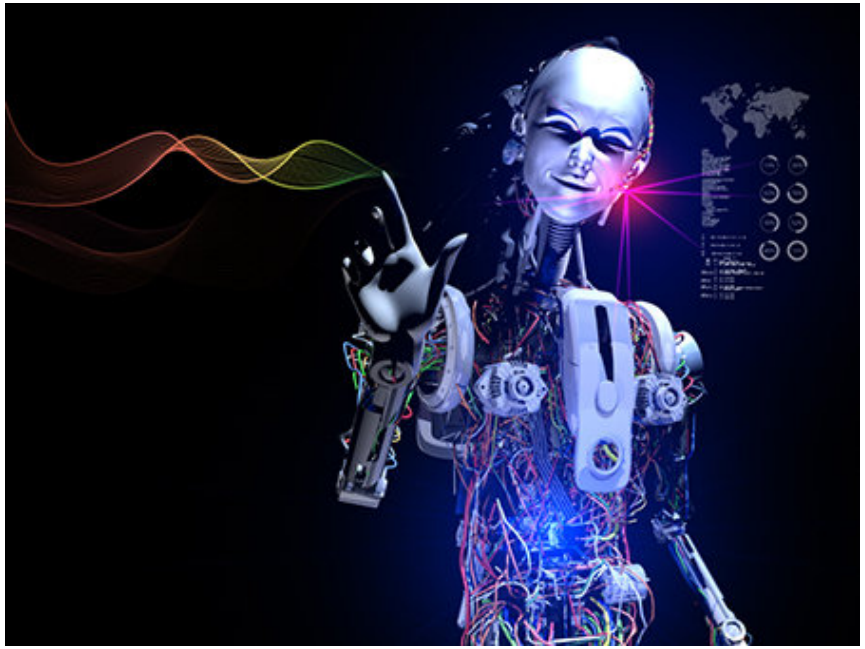
  Power robots, computers electronics
- ✧ No Realignment between source and device necessary
- ✧ One coil can recharge any device in that is in range, as long as the coils have the same resonance frequency
- ✧ Transfer power only when needed
- ✧ Efficiency in the 45 - 95 %

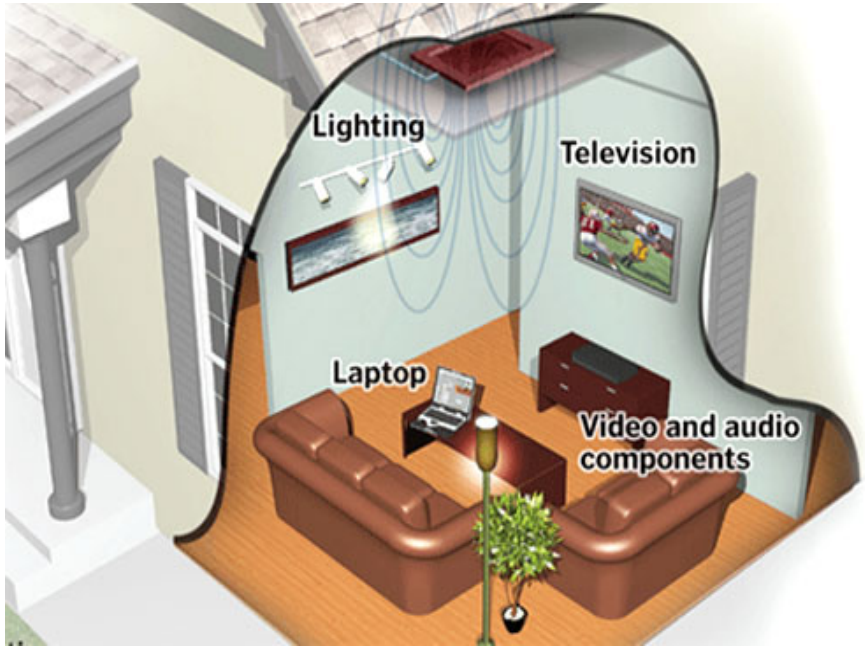
https://arxiv.org/vc/physics/papers/0611/0611063v1.pdf

Wireless Electricity
(need of WITRICITY)

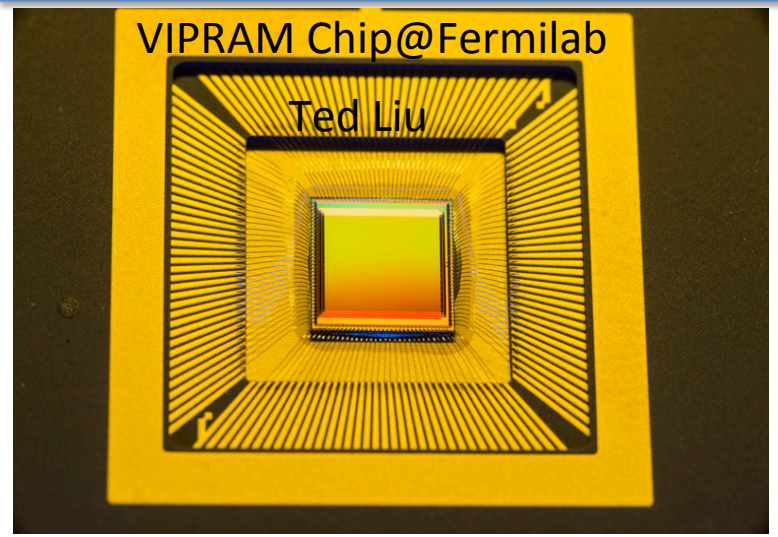
Applications:

- **Consumer electronics** – mobile device charge, wireless batteries, retail packaging….
- **Automotive** – In-vehicle mobile device charging
- **Industrial** – Wireless charging for robotics, direct powering of sensors
- **Medical** – through-the-skin charging for implantable devices





Vertically Integrated Pattern Recognition Associative Memory (VIPRAM)

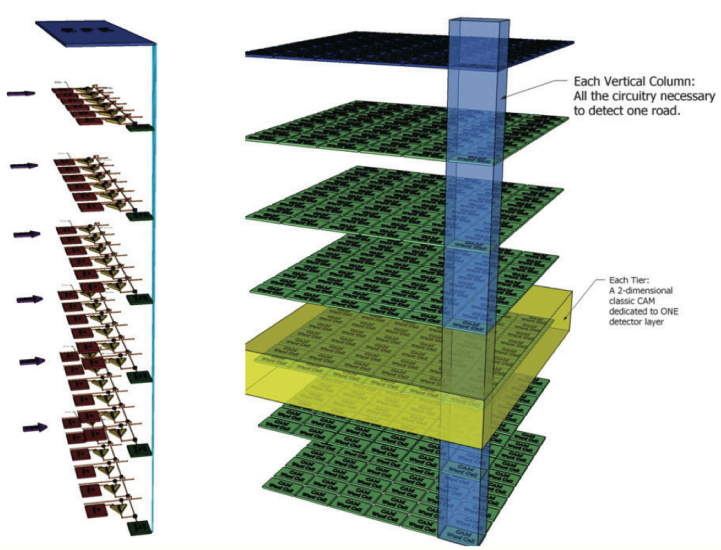


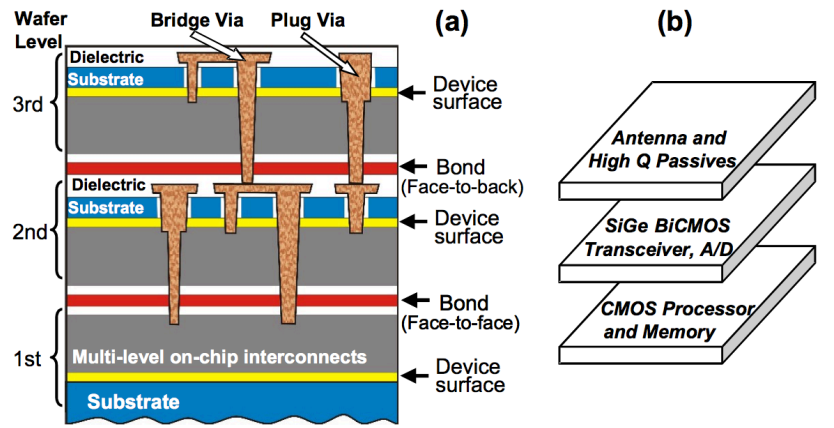
As Moore law is approaching is limits, it is expected that 3D will be the next scaling engine.

Associative memory chip:

- Fast pattern recognition for fast track triggering at ATLAS and CMS

Through Silicon Vias between VIPRAM and Transmitter





Next step R&D

Planned for the Next Generation of Detector System

Main requirements:

- Power consumption
- Space
- Reliability
- Some sub-systems has to be extremely radiation hard

A major focus on this R&D will be on the power consumption, that require a thorough understanding of the final System application

Transceiver chip forseen to grow in complexity and functionality as we explore the possibilities

Significant technological evolution can be expected in the coming years

Which technology to use and where to use it in the detector depends on many factors

- **Radiation hardness**
- **Speed**
- **Analog performance (dynamic range or feature size)**

New optimized detector design

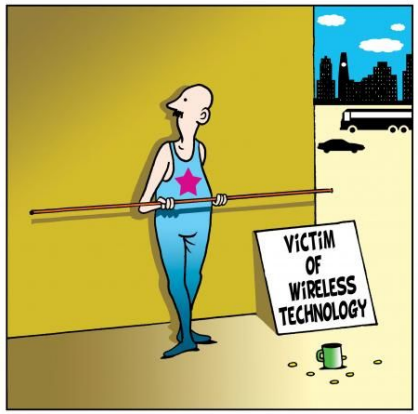
Next step R&D

Substantial dedicated effort to qualify the system, technology and optimize the design is required

A rethinking of the existing detector is also required, to avoid signal attenuation in detector modules.

The wireless technique will bring an elegant answer to the need of our ever-growing detectors:

- Reduction of the number of cables/connectors resulting in the reduction of the dead material, of geometrical efficiency and cost.
- High data transfer from highly granular detectors.
- Complex topologies for fast triggering



As a result of this R&D:

- A optimized demonstrator to assess feasibility and performance, refine the estimate of the required data transfer rate and establish a solid basis to design the final system.

Summary and Outlook

- ✓ A third option (Wireless, optical and Wire) is described.
- ✓ MmWave technology presented as a possible solution for current bandwidth limitations of LHC and maybe other detector facilities

There is a lot and increasing interest for this development on different levels

Technical Paper sent and evaluated by CERN Scientific Committee

LHCC Committee meeting Closed session May 11 2017

Our Technical Paper was Very well taken, only with minor comments!

Final outcome/approval September/December 2017

The future of connectivity is wireless. The HEP community not an exception

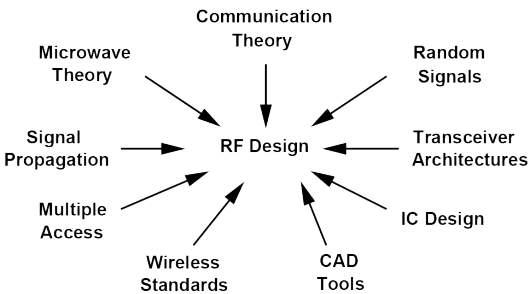
Questions?

Back-Up

Disiplines, requests and trade-offs involved in RF-Design

System Considerations:

- Frequency
- Bandwidth
- Conversion gain or loss
- Return Loss
- Spurious Response
- Linearity
- Gain Compression (P1dB)
- Third-Order Intermodulation Distortion (IP3)
- Power Consumption
- Complexity



Dynamic range

$$Noise\ Floor = \underbrace{-174dBm}_{\text{kT limitation}} + NF + 10\log \underbrace{BW}_{\text{Bandwidth}}$$

SFDR: Spurious free dynamic range
The input power range over which third order inter-modulation products are below the minimum detectable signal level.

$$SFDR = \frac{2}{3}\left(IIP_3 - Noise\ Floor\right) - SNR_{min}$$

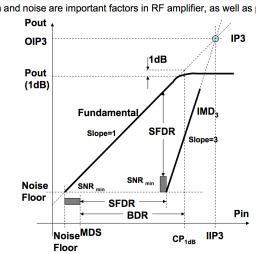
BDR: Blocking dynamic range

$$BDR = P_{1dB} - Noise\ Floor - SNR_{min}$$

MDS: Minimum detectable signal level= Noise Floor +SNR_{min}

Input and output characteristics

Distortion and noise are important factors in RF amplifier, as well as power and gain.



Non-linearity

CP_{1dB}: The input level at which the small signal gain has dropped by 1dB.

$$CP_{1dB} = \sqrt{0.145\left|\frac{\alpha_1}{\alpha_3}\right|}$$

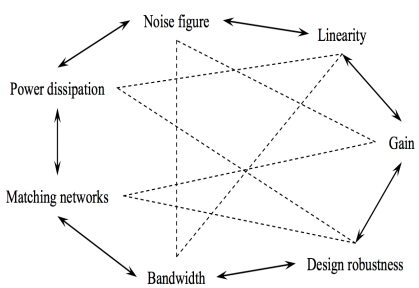
IMD3: The third order inter modulation term

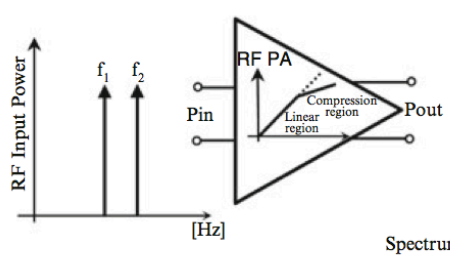
IP3: The metric third order intercept point. It is the point where the amplitude of third order inter modulation is equal to the that of fundamental.

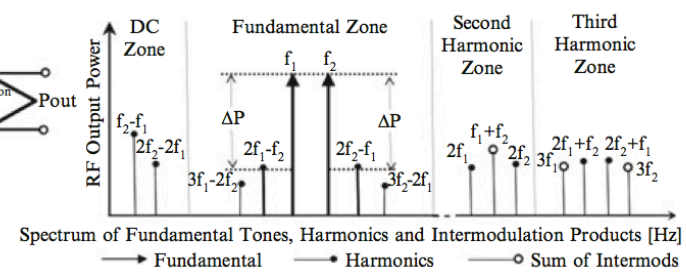
$$A_{IP3} = \sqrt{\frac{4}{3}\left|\frac{\alpha_1}{\alpha_3}\right|}$$

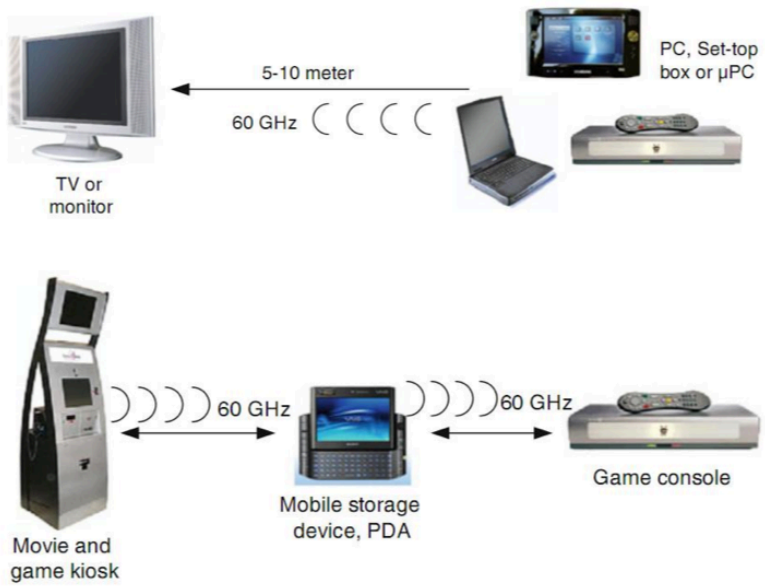
IIP3: Input referred intercept point
OIP3: Output referred intercept point

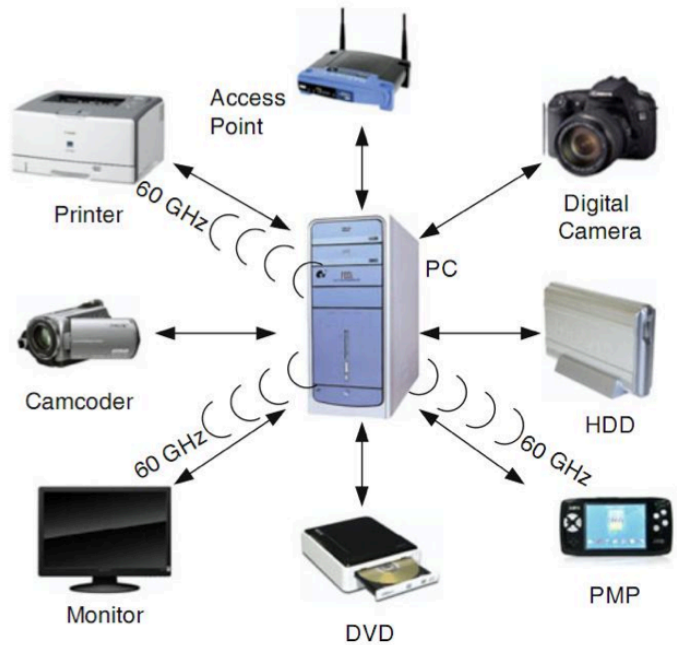
$$P_{out} - IMD_3 = 2\cdot\left(IIP_3 - P_{in}\right)$$

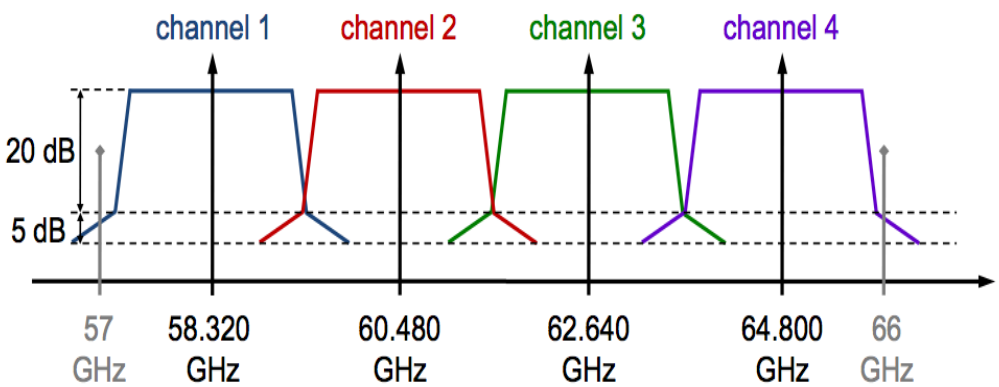


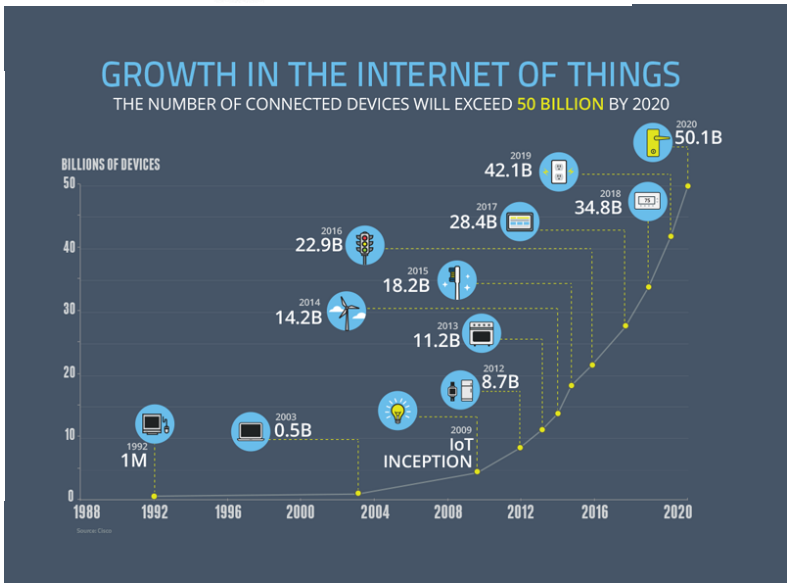


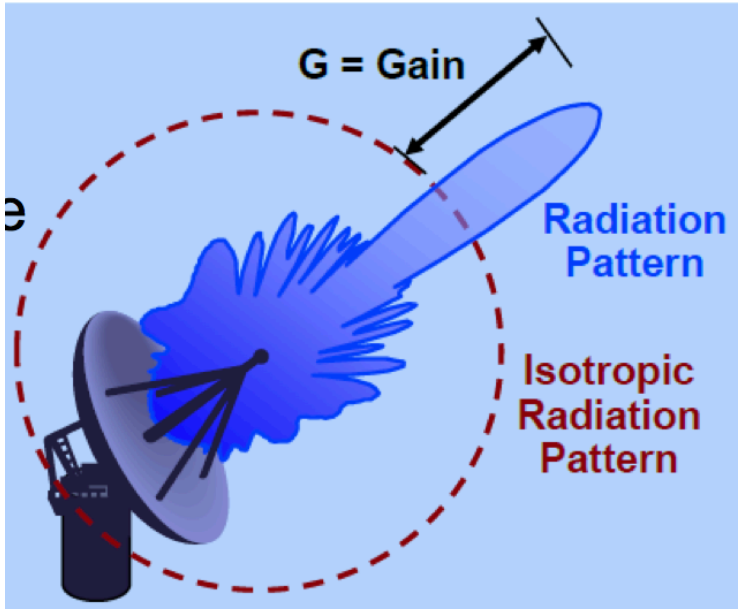


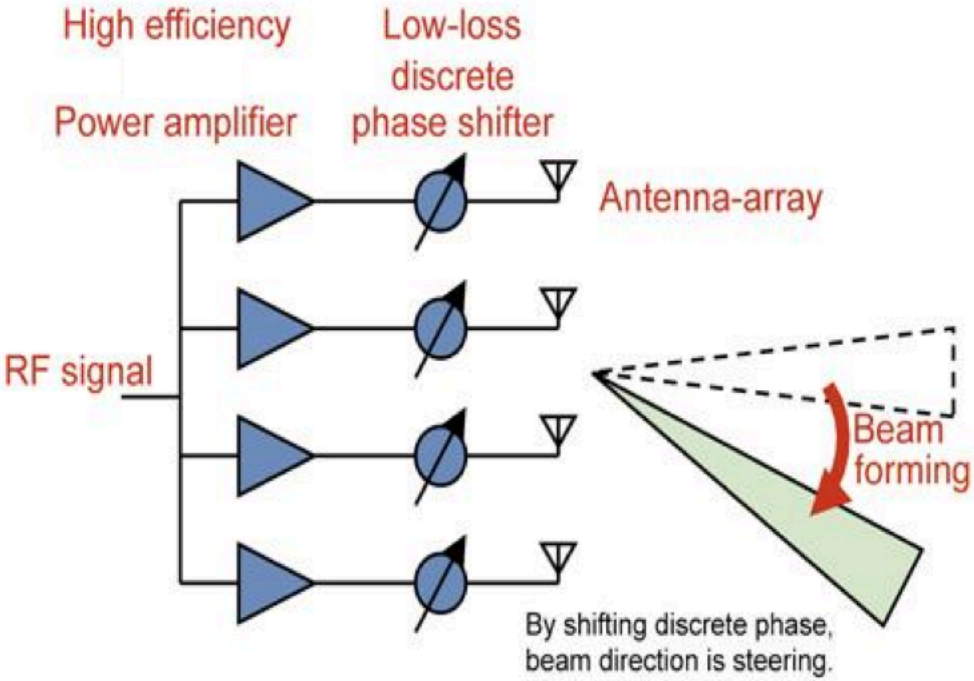

5-10 meter
60 GHz
PC, Set-top box or µPC
TV or monitor
60 GHz
60 GHz
Movie and game kiosk
Mobile storage device, PDA
Game console


Access Point
Printer
60 GHz
Digital Camera
PC
Camcoder
HDD
60 GHz
60 GHz
Monitor
DVD
PMP


channel 1
channel 2
channel 3
channel 4
20 dB
5 dB
57 GHz
58.320 GHz
60.480 GHz
62.640 GHz
64.800 GHz
66 GHz


GROWTH IN THE INTERNET OF THINGS
THE NUMBER OF CONNECTED DEVICES WILL EXCEED 50 BILLION BY 2020
BILLIONS OF DEVICES
1992 1M
2003 0.5B
2009 IoT INCEPTION
2012 8.7B
2013 11.2B
2014 14.2B
2015 18.2B
2016 22.9B
2017 28.4B
2018 34.8B
2019 42.1B
2020 50.1B
1988 1992 1996 2000 2004 2008 2012 2016 2020


G = Gain
Radiation Pattern
Isotropic Radiation Pattern


High efficiency
Power amplifier
Low-loss discrete phase shifter
Antenna-array
RF signal
Beam forming
By shifting discrete phase, beam direction is steering.